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Information During Instrument
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SUMMARY

A simulation study was undertaken to evaluate flight operations using cockpit display of traffic information (CDTI) in a conventional jet transport aircraft. In this study, eight two-man flight crews of airline pilots participated as test subjects flying simulated terminal area approach and departure operations under instrument meteorological conditions (IMC) with and without the presence of CDTI. A fixed-base cockpit simulator configured with a full complement of conventional electromechanical instrumentation to permit full workload operations was utilized. A postulated CDTI system, based on an experimental airborne collision avoidance traffic sensor, was modeled in the simulation. The traffic information was displayed on a color cathode-ray tube (CRT) mounted above the throttle quadrant in the typical weather radar location, with a transparent touchpanel overlay utilized for pilot interface. Air traffic control (ATC) simulation, including an experienced controller and full partyline radio communications with prerecorded traffic scenarios, provided a realistic traffic environment for evaluation of CDTI tasks. Identical scenarios were flown with and without CDTI to evaluate pilot-controlled self-separation and traffic situation monitoring tasks. Cockpit procedures and workload were analyzed through pilot ratings and recorded audio, video, and digital data of each simulation run. Postulated impact of CDTI on airport capacity, aircraft operating procedures, and ATC were also included in the evaluation.

Results of the study revealed that the CDTI was well received by the test subjects as a useful system which could be incorporated into an existing jet transport cockpit. The display of traffic information presented the crew with additional duties and procedures to perform. Cockpit workload was increased with active CDTI tasks; however, all test subjects rated the increase to be acceptable. Crew coordination and consistent operating procedures were identified as important considerations in operational implementation of traffic displays. The possibility of CDTI-induced distraction from existing procedures was further identified as a potential problem. Crew training, experience level, and alert and warning features were cited as factors affecting the distraction potential of CDTI.

In-trail self-spacing approach tasks performed in this study resulted in mean interarrival time at the runway threshold which was 7.2 seconds less than that achieved for identical scenarios flown without CDTI. Dispersion of arrival times also showed a decrease in standard deviation of 6.6 seconds when the pilots performed their own spacing. These results suggest the possibility of increased airport capacity with the use of CDTI self-spacing procedures. Actual capacity gains would be dependent on the mix of aircraft types, runway configurations, percentage of aircraft performing self-spacing, and the spacing criteria utilized by the pilots and controllers.

The fuel efficiency of aircraft performing CDTI approach self-spacing was found to be adversely affected by early issuance of spacing clearances and by the lack of adequate spacing guidance during the initial descent segment. Operational CDTI self-spacing procedures would need careful development in order to minimize fuel penalties associated with these tasks.

ATC radio communications decreased by 12 percent for the CDTI approach self-spacing scenarios. This reduction reflected the fewer vectoring instructions

required by the self-spacing aircraft. For the departure scenario, pilot/controller coordination requirements resulted in a 25-percent increase in radio communications. Design of the procedures for coordinating CDTI self-separation between pilots and controllers has a primary affect on the ATC impact of CDTI. Compared with the baseline, no additional communications from pilots questioning ATC concerning traffic on the CDTI were encountered during any of these tests.

INTRODUCTION

Recent advances in digital avionics and electronic technology are providing an increasing amount of information available for use in the cockpit of modern jet transport aircraft. Incorporation of this new technology and development of crew procedures for effective and safe utilization of the new information is a subject of great concern in the aviation community. One such technology is the graphic presentation of surrounding traffic on an electronic display in the cockpit.

The concept of cockpit display of traffic information (CDTI) was first proposed in the 1940's as a television broadcast of the air traffic control radarscope display (ref. 1). Technical deficiencies and the lack of clear benefits associated with this concept prevented continuation of those early efforts. In the 1970's, numerous simulation studies identified several possible benefits associated with the active use of CDTI. Most notable were the efforts by the Massachusetts Institute of Technology as summarized in reference 2. Among the benefits cited in these studies were increased airport capacity, reduced demand on controllers, improved situation awareness for pilots, and enhanced safety of flight.

A joint program was undertaken in the late 1970's by the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) to explore potential CDTI applications under realistic operational and workload conditions. As a part of this program, the Langley Research Center has been investigating CDTI applications in the operation of transport aircraft through the use of piloted simulation studies. These studies (refs. 3 through 5) utilized a part-task cockpit simulator to evaluate CDTI display requirements and active self-separation tasks in the context of terminal-area approach operations.

The primary objective of this study was to extend the part-task studies into a full-system environment involving airline pilots and a comprehensive air traffic simulation. The focus of this effort was on cockpit procedures and workload under full-workload conditions. Research issues included crew duties, CDTI impact on existing procedures, self-separation procedures, airport capacity, aircraft fuel efficiency, and CDTI impact on ATC. Of particular interest were terminal-area approach operations which typically are the most demanding on pilots and controllers and generally account for the majority of delays experienced at major airports. In-trail self-spacing methods involving time-based separation criteria developed in reference 5 were adapted for use in this study.

The research method used in this study was a comparative analysis of pilot workload and performance with and without CDTI. Generic scenarios of approach and departure operations at Stapleton International Airport in Denver, Colorado, were devised based on current operations in IMC. Airline test subjects flew the scenarios without CDTI in order to establish baseline performance, procedures, and pilot ratings of workload. The scenarios were repeated with CDTI used for monitoring and/or self-separation tasks. Data taken during the tests consisted of subjective pilot

ratings and comments as well as digital recording of flight parameters and audio and video recordings of cockpit activities during each simulation run.

RESEARCH SYSTEM

This study was conducted by using a piloted cockpit simulator in conjunction with an air traffic control simulation. The research system was designed to provide the crew of the cockpit simulator with a realistic, full-workload environment. A block diagram of the research system is shown in figure 1. The host computer was a CDC® CYBER-175 system, which contained the mathematical algorithms for the piloted simulator and controlled the correlation and distribution of traffic and display data to the cockpit and controller station. Separate graphics computers were used to generate the CDTI picture in the cockpit and the controller scope picture at the controller station. Communication between the cockpit simulator and the controller station was handled through a radio-frequency matching system which permitted audio communication only when both the controller and cockpit were tuned to the same frequency.

Cockpit Simulator

A fixed-base, nonvisual cockpit simulator configured as a conventional, two-engine jet transport aircraft was used in this study (fig. 2). The aircraft dynamics modeled were those of a Douglas DC-9 Series 30 aircraft. Nonlinear aerodynamic data and standard day atmospheric effects were included in the simulation model. Aircraft dynamics, navigation, and flight instrumentation algorithms were contained in the CDC CYBER-175 host computer. A full complement of cockpit electromechanical instrumentation was provided, with all major systems functional including autopilot, dual flight directors, navigation, and communication radios. Subsystems, such as hydraulics and electrical systems, were modeled to the extent necessary to provide normal in-flight indications to the crew. The cockpit configuration and instrument arrangement were based on that used by a major domestic airline. Minor adjustments could be made in instrument type and location in order to accommodate test subjects of different airlines.

Air Traffic Control Simulation

The controller station shown in figure 3 was utilized to provide the air traffic control simulation for this study. The focal point of the station was a 20-inch-diameter CRT display which presented an electronic map of the simulated airspace to the controller. The display format and symbology used to represent the traffic were a simplified version of that provided on a control scope at the Denver Terminal Radar Approach Control facility (TRACON) located in the control tower at Stapleton International Airport. The display was oriented north up (either magnetic or true at controller discretion) and could be centered about various locations in order to simulate the different control sectors in the Denver area. The single control station was used to represent all air traffic control sectors used in the study. An experienced air traffic controller manned this station throughout these tests.

Simulation of different control sectors using a single control station was handled by a radio-frequency matching system as illustrated in figure 1. Each control sector was assigned a specific radio frequency for communication with the aircraft flying in that sector. The controller would select the frequency of the

control sector he was currently simulating on a radio tuner mounted above his control display. This frequency would be compared with the frequency selected by the active radio in the cockpit simulator to determine whether the audio channel should be on or off. When the frequencies matched, the controller and cockpit crew could communicate. In addition the controller was presented a display of the actual frequencies to which the crew had tuned their radios and an indication when the microphone was keyed on a particular frequency. Using an override switch, the controller could then bypass the radio matching system and talk directly to the crew. This feature was used when the crew was talking on a frequency which was not the one assigned to them but was a legitimate frequency for another sector in the Denver area. The controller would mimic the other sector and inform the crew to tune the proper frequency.

Prerecorded traffic data were used to represent the other aircraft flying in the scenarios. The CYBER-175 would read the traffic tape at 1-second intervals, process the data, and send them to the controller station graphics computer at 4-second intervals (the approximate update rate for terminal area ground surveillance radars). The traffic data were also sent to the CDTI graphics computer after processing by the airborne traffic sensor simulation model contained in the CYBER. The controller would use a script of communications with the other aircraft, correlated with scenario time and radio frequency, in order to provide background partyline communications with the aircraft. With a display of the current scenario time and this script, the controller would read a communication to another aircraft at the proper time if the cockpit crew had a radio tuned to the frequency indicated on the script for that particular communication. The controller would also read the responses for the other traffic in order to provide the complete partyline simulation.

EXPERIMENT DESIGN

CDTI Description

The traffic information was displayed to the crew on a color cathode-ray tube (CRT) located above the throttle quadrant at approximately the same location as a standard weather radar unit. The display measured 9 inches across the diagonal and was fully covered by a transparent membrane-type touchpanel. Pilot interface with the CDTI was handled with preprogrammed touchpanel functions on the display.

The format used for the CDTI is illustrated in figure 4. The top and bottom 10 percent of the display contained mode control buttons and alert warning information. The remaining 80 percent of the CDTI was a horizontal plan view display of own-aircraft and traffic symbology superimposed on a navigation map.

The navigation map presented a graphic representation of major navigation aids and route structure which would translate and rotate smoothly about the own-aircraft symbol in a track-up orientation. The map was composed of the four arrival routes into the Denver terminal area, with navigation intersections shown along each route. (See fig. 5.) In addition, the runway complex at Stapleton International Airport, with extended centerline and outer marker location for runway 26L, was also drawn on the map. Scaling of the map display was accomplished by using the map IN/OUT buttons located in the lower right corner of the display. (See fig. 4.) The available map scales were 5, 10, 15, 20, 25, 50, and 100 nautical miles. Scale factor would decrease by touching map IN ("zoom in" on a smaller portion of the display) and increase by touching map OUT ("zoom out"). Current map scale was given in the upper right portion of the display in terms of the distance in nautical miles from own aircraft to the top of the map display.

The symbol representing own aircraft was fixed on the display, centered horizontally with two-thirds of the display area in front of the symbol. The tip of the symbol represented the current position of own aircraft. A curved predictor vector extended from the own-aircraft symbol indicating the ground track own aircraft would follow at current groundspeed, heading, and turn rate. The end of the predictor vector indicated the predicted future position of own aircraft in 60 seconds. Instantaneous track was presented as a dashed line extending from the tip of the own-aircraft symbol to the top of the map display. Predictor reference marks were drawn on each side of the track line to highlight the length of the 60-second curved predictor during straight-ahead or minimal turning situations. A fixed-range reference arc surrounded the own-aircraft symbol indicating a horizontal distance of 3 nautical miles from own aircraft. A numeric data tag, giving own-aircraft groundspeed (tens of knots) and altitude (hundreds of feet), was located immediately below the own-aircraft symbol.

A simulation model of the enhanced Traffic Alert and Collision Avoidance System (TCAS II) was used to measure and track the traffic (ref. 6). Traffic information was presented on the display as symbols indicating the last measured or tracked position of the traffic. The shape of the traffic symbol encoded relative altitude and tracking status as illustrated in figure 6. The traffic symbols remained fixed to the map until an updated position was determined by the TCAS simulation model. An alphanumeric data tag was available for each traffic symbol which provided flight identification (e.g., EA806 in fig. 4), groundspeed (tens of knots), and altitude (hundreds of feet). The groundspeed was determined from the TCAS tracking of the traffic and was therefore only available for those aircraft being actively tracked. In addition, a straight-line 60-second predictor vector was available for tracked traffic. For traffic not being tracked, a groundspeed of zero appeared in the data tag and a predictor vector could not be displayed.

Color coding of display symbology was utilized to enhance readability. Navigation map features, including the names of intersections, were drawn in dark blue against the black background. Inactive mode control function buttons and labels were white, with those for the active mode colored green. Own-aircraft symbology, including track line, predictor, range arc, and data tag, were a bright cyan (light blue). Traffic symbology was drawn in white, with the exception of the LEAD-aircraft symbology (defined in the following paragraphs) which was magenta. In addition, the symbologies for traffic determined by the TCAS simulation model to require a traffic advisory were specially coded for quick recognition by the crew. The three levels of TCAS traffic advisories which could be issued were proximity, threat, and resolution. Traffic with a proximity advisory would remain white; however, the symbol would flash on and off at approximately 2 cycles per second. The symbologies for threat advisory traffic were color-coded a flashing yellow, and those for resolution advisory traffic were flashing red. A complete description of the TCAS advisories can be found in reference 6. The actual resolution advisories determined by the TCAS (such as "climb" and "descend") were not presented to the crew in this simulation.

The transparent touchpanel mounted over the CRT was used for all pilot interface with the display. Five traffic and two map scale functions were provided as labeled buttons on the top and bottom edges of the display as seen in figure 4. Selection of a desired function was accomplished by touching the corresponding labeled box. The label and box outline of the selected function would change to green signifying an active mode, with any previously selected function returning to the inactive mode color (white). After the desired traffic function was selected, touching a traffic symbol resulted in the operation being performed on that symbol. The function mode would become inactive following a successful operation to prevent accidentally

touching the same or different traffic symbols several times while in the same mode. A description of the five traffic functions is given in the following paragraphs.

TRAF (traffic selection): This function reset the display to default conditions. Symbologies for all traffic within range of the TCAS sensor (approximately 25 nautical miles) were displayed, with predictor vectors and data tags removed from all traffic symbols. Touching traffic symbols while in this mode did nothing.

DEL (traffic deletion): This function was used to delete traffic symbols from the display. Traffic deleted in this manner could be returned to the display by pressing TRAF. Any traffic symbol with a TCAS advisory was automatically displayed and could not be deleted.

PRED (predictor): This function was used to add or remove a traffic predictor vector. Only traffic being actively tracked could have predictors. As noted above, all predictor vectors could be removed simultaneously by touching the TRAF function.

TAG (data tag): This function was used to add or remove the alphanumeric data tag adjacent to the traffic symbol. Once again, the TRAF function could be used to remove all data tags.

LEAD (lead aircraft): This function designated a traffic symbol to be the lead aircraft for the in-trail self-spacing task. A complete description of the self-spacing task and display symbology used for the lead aircraft is given in the section "CDTI Self-Separation."

Air Traffic Scenario

The air traffic environment modeled for this study was an area within a radius of approximately 100 nautical miles of the Stapleton International Airport in Denver, Colorado. Approach and departure scenarios at the Stapleton Airport were simulated for instrument weather conditions. The approach scenarios began with the simulator at cruise altitude prior to initiating descent into the Denver terminal area and concluded with an instrument landing system (ILS) approach to runway 26L at Denver. The departure scenarios began with takeoff from runway 35L at Denver, followed by a south departure from the Denver terminal area. Traffic aircraft were inserted into the scenarios by using a prerecorded traffic generation technique. A complete description of the air traffic scenario generation technique, as well as the traffic environment used in this study, may be found in reference 7.

Crew Procedures

The test subjects used in this study were active pilots employed by two major United States domestic airlines. All pilots were qualified to fly DC-9 Series 30 aircraft with their respective airlines. Each test crew, consisting of two pilots from the same airline, was instructed to observe the normal operating procedures of their airline. Operating manuals, checklists, and speed charts used during the tests were the same as those used by the airline which employed the test subjects. In addition, specific instructions describing the approach and departure scenarios were provided the crew during briefing sessions prior to the simulation runs. A copy of these pilot instructions may be found in appendix A. The crew member acting as Captain was further instructed to be the flying pilot during all the data runs, with

the First Officer performing the nonflying duties. During practice sessions, the Captain and First Officer were permitted to alternate flying duties.

CDTI Self-Separation

The normal crew flight duties were augmented by special procedures for utilization of the CDTI display information. These procedures were designed to apply an extension of visual separation procedures to nonvisual situations where separation could be displayed on the CDTI. Terminology and rules for CDTI self-separation were developed and discussed with the test subjects prior to the simulation runs. The written procedures, as provided the test subjects, may be found in appendix B.

During the course of the simulation testing, the test subjects were given two situations where the CDTI self-separation procedures were applied. The first situation was an approach scenario where the crew was instructed to establish and maintain a specified spacing interval behind another aircraft on approach to the same landing runway. This task is referred to as approach in-trail spacing. The second situation was a departure where the crew was instructed to avoid specific approaching aircraft during climbout after takeoff. For both situations, the crews were given general briefings on interpretation of CDTI display information and suggested actions; however, crew coordination and implementation tactics were developed by each crew during training sessions.

The approach in-trail spacing task employed a separation technique referred to as "constant-time-delay spacing," as described in reference 5. Essentially, this technique displays the desired location of own aircraft on the CDTI for a specified constant-time interval behind the designated lead aircraft. As described in reference 5, this time-based spacing technique has been found to be operationally suitable for the descending, decelerating approach-to-landing situation for similar performance aircraft.

Figure 7 shows a drawing of the information displayed on the CDTI to assist the pilots with the in-trail spacing task. This information was displayed for the traffic symbol selected using the LEAD function button. As shown in the figure, a history trail of past position dots was displayed for the lead aircraft. The dots represent previous map positions of the lead aircraft at 4-second intervals for a total history of 100 seconds. A spacing box was drawn at the point on the history trail equivalent to the specified 80-second-spacing time interval. This box represented the desired location of own aircraft in order to maintain the specified time interval behind the lead aircraft. The top and bottom solid lines of the spacing box provided a 15-second buffer about the desired time. A numeric data tag giving the speed and altitude of the box and a speed reference arc were provided to aid the pilot in capturing and maintaining position in the box. The display distance from the desired spacing location to the speed reference was equal to the instantaneous groundspeed of the box multiplied by 60 seconds. The relative positions of the speed reference arc and the tip of the own-aircraft 60-second predictor vector provided the pilots with a quick reference for maintaining proper spacing. The recommended technique was to keep the tip of own-aircraft predictor on the speed reference arc if the own-aircraft symbol was anywhere within the spacing box, otherwise to use the numeric groundspeed tags of own aircraft and the spacing box in order to establish a closure rate on the box. In all cases, the airspeed limits of own aircraft took precedence over the spacing task.

Test Conditions

A series of test conditions was devised to provide a comparative analysis of present-day approach and departure operations with various levels of CDTI usage. The five combinations of terminal area operation and CDTI usage level which were tested are given as follows:

Condition	Terminal area operation	CDTI usage level
1	Approach	No CDTI
2	Approach	CDTI monitoring
3	Approach	CDTI self-separation
4	Departure	No CDTI
5	Departure	CDTI self-separation

The major emphasis of this study was on the first three conditions involving approach operations. Each of the three conditions employed the identical approach traffic scenario and initial conditions for the piloted cockpit simulator. Condition 1 was the baseline approach with the test subjects flying the final cruise, descent, and approach to landing at Denver as would be flown in today's ATC environment. The traffic display was turned on for the crew to utilize in a monitoring role for condition 2, with the crew given a self-separation task involving in-trail following of another aircraft for condition 3. Although each of these conditions utilized identical approach traffic scenarios, this situation was not revealed to the test subjects. In addition, different aircraft identifications were assigned to the traffic aircraft on each run in order to assist in masking the similarity of the scenarios from the test subjects. Also, departure traffic aircraft displayed during replication runs of condition 3 were varied to present a different traffic picture to the plots.

Conditions 4 and 5 were added to the test matrix in order to provide a preliminary assessment of CDTI utilization during departure operations. Pilot instructions and CDTI procedures were less specific than for the approach conditions, with the data analysis being of a more qualitative nature. The baseline departure (condition 4) consisted of the takeoff and initial climb segments of a flight from Denver. Condition 5 added CDTI and a self-separation task to the baseline departure scenario. The self-separation task was to utilize the traffic display to identify and avoid specified traffic during the departure. The scenario was designed to require pilot action in order to avoid conflict with the traffic.

A total of 16 airline pilots from two major United States domestic airlines participated as test subjects in this study. The test subjects were grouped into 8 crews of two pilots each, with only pilots from the same airline flying together as a crew. A sequence of simulator familiarization, CDTI training, and data runs was conducted over a 2-day period with each crew. Table I provides the training and test run sequence which was observed for the crews. The amount of time devoted to specific training sessions was not consistent between the test crews because of time constraints within the 2-day testing schedule. In addition, the test subjects were allowed additional training time with the CDTI if they felt uncertain about using or understanding the information on the display. Table II shows the training and data runs actually completed by each of the eight test crews.

RESULTS AND DISCUSSION

Results from this study were obtained in the form of pilot opinions from questionnaires and debriefing sessions as well as quantitative measures of airplane state variables and systems status parameters coupled with detailed audio and video cockpit recordings of each data run. The complexity of the research issues and limited number of data runs and test subjects prevented a rigorous statistical analysis of the results. Rather, a more subjective approach was applied to the data analysis. The major research issues were addressed by using pilot questionnaires following each data run and at the conclusion of all testing. Pilot comments on these as well as issues not covered in the questionnaires were obtained during debriefing sessions. Finally, the recorded data were reviewed to supplement the subjective results. The questionnaires and rating scales used in this study may be found in appendix C.

Cockpit Procedures Considerations

A primary concern over the introduction of cockpit traffic displays is the impact of such information on cockpit duties and procedures. This issue is twofold, namely, what is the effect on existing procedures, and what new procedures are required to effectively utilize the traffic information. The test scenarios in this study were designed to address these questions from the standpoint of a conventional two-crew jet transport cockpit configuration with CDTI added as a retrofit system.

Crew duties.- The flight crew of a DC-9 class aircraft consists of a Captain, who is in command of and responsible for the aircraft, and a First Officer. Although, either crew member may actually fly the aircraft, all data runs in this study were conducted with the Captain as the flying pilot.

The division of duties between the flying and nonflying pilots was generally the same for all the test crews in this study. The flying pilot performed the basic flight control either manually or with autopilot functions. In addition, the flying pilot would call for and respond to checklists, conduct approach briefings, and monitor subsystems and communications on a time-available basis. The nonflying pilot would handle ATC communications, tune radios, read and respond to checklists, monitor subsystems, and provide backup on primary flight parameters and navigation. The amount of interaction between the flying and nonflying pilots varied between crews and between runs for the same crew.

The addition of traffic information presented the crew with a new system to operate and monitor when necessary or desired. Specific crew duties associated with the traffic display were dependent on the flight situation and mode of traffic separation being employed. For situations where traffic separation was provided by ATC, the traffic display was merely a monitoring device with no specific function. In this case, both pilots would utilize the device on a time-available basis in order to keep abreast of the traffic situation and identify traffic pointed out by ATC. Typically the nonflying pilot would operate the controls on the traffic display, often at the request of the flying pilot. When the crew was given a self-separation task, operation of the traffic display became a necessity. In this case, the flying pilot would use the traffic display for speed, heading, and possibly altitude guidance in order to establish or maintain traffic separation. Actual operation of the display (map scaling, traffic selection, etc.) was still typically handled by the nonflying pilot. CDTI operations did not affect the nature and extent of crew interaction and coordination.

CDTI impact on existing procedures.- At the conclusion of the simulation runs, the test subjects were asked to assess the impact of CDTI on their normal operating procedures. This assessment was in the form of rating the potential for distraction from normal duties as well as enhancements to procedures afforded by the traffic information.

Figure 8 shows the pilot ratings of the likelihood that a traffic display would be a distraction from normal duties. As seen in the figure, there was a wide range of opinions concerning the distraction potential of CDTI, with all but two of the pilots indicating some likelihood for distraction. Most of the pilots commented that the traffic display was a compelling device which drew their attention for longer periods of time than necessary for the task. The novelty of the device was cited as the prime reason for this distraction, with most pilots expressing the opinion that this situation would improve with more exposure to the system. It should be noted that 14 of the 16 test subjects in this study had virtually no prior experience with electronic map presentation such as that provided by the traffic display in this study.

All major procedures involving checklists were found to be unaffected by CDTI usage. These procedures are triggered by specific events, such as initiating descent or lowering landing gear, and were accomplished routinely regardless of CDTI tasks. The effect of CDTI on pilot recognition of a problem in one of the subsystems of the airplane was not addressed in this study. However, review of video recordings of the cockpit during the data runs did show the pilots spending a good deal of time watching the traffic display, which might suggest less time being spent monitoring systems. As discussed previously, this situation was primarily the result of the novelty of the display and may not be representative of actual operations.

A potential adverse effect of CDTI was in the flying pilot's ability to incorporate the traffic information into his primary flight instrument scan. Distraction from primary flight instruments can result in excursions from desired flight conditions such as altitude and airspeed which are not noticed or compensated for by the pilot in a timely manner. To analyze the pilot's performance of controlling altitude and airspeed, time histories of each data run were developed which compared actual altitude and airspeed with the desired values. The desired altitude was defined as the ATC-instructed altitude ± 250 feet. A deviation beyond the 250-foot tolerance for more than 5 seconds was recorded as an altitude excursion. Transitions between assigned altitudes were not included in the analysis. Airspeed excursions were recorded when the airspeed exceeded 5 knots above or below the maximum and minimum airspeeds, respectively, for more than 5 seconds. The magnitude of the airspeed excursion was defined as the peak value which occurred during the excursion. The maximum airspeed was chosen to be the maximum allowable airspeed for the aircraft's current flap configuration. Minimum airspeed was defined as the maneuvering speed given in the landing speeds reference chart for the current flap configuration and projected landing weight. ATC-assigned speeds were not considered in the analysis since speed control was not uniformly applied to all simulation runs and the self-separation runs with CDTI had no ATC-assigned speeds.

Results of the altitude analysis showed that no excursions occurred in any of the data runs with or without CDTI. Several pilots, however, commented that altitude control was more difficult when they were using the traffic display for self-separation. The altitude alerting system on the airplane, which includes audio and visual cues at 750 feet and 250 feet prior to reaching a preselected altitude, was instrumental in alerting the pilots to an approaching assigned altitude. On several occasions, these alerts effectively drew the attention of the pilots back to the

primary flight instruments and prevented a probable altitude excursion as the airplane reached a new assigned altitude. A few of the pilots suggested incorporating an altitude alert on the traffic display to insure pilot recognition of approaching assigned altitudes during climbs and descents. Once established at an altitude, the pilots had no trouble holding altitude either manually or with the autopilot.

Airspeed excursions were recorded during 13 of the approach data runs. A trend of increasing airspeed violations with increasing CDTI usage was evident. Figure 9 shows the average frequency of airspeed excursions as a function of CDTI usage level. The magnitude of the speed excursions was also found to increase with increasing CDTI usage as shown in figure 10. Review of cockpit video recordings showed the pilots to be often preoccupied with watching the traffic display at the times when the airspeed excursions occurred. In all cases, the airspeed excursions were at the minimum airspeed condition. The pilots were inadvertently allowing the airplane to reach a lower airspeed than it should for the flap configuration they were using. Although no hazardous situations were encountered, the potential for a stall during an abrupt maneuver was increased.

The primary factor which contributed to the problem of excursions below minimum maneuvering speed was identified as a distraction from scanning the airspeed indicator. Several pilots suggested an airspeed indication with some alerting feature be included on the traffic display in order to alleviate this problem.

Positive effects of CDTI on normal procedures were cited by several of the test subjects. Most notably was the improvement in traffic awareness and flight planning afforded by the traffic display. Several of the pilots stated that knowledge of the traffic flow was an integral part of their mental preparation and planning for airspeed, altitude, and heading changes. Without CDTI, these pilots relied on voice communications (ATC partyline) to create a mental image of the traffic situation. With CDTI, this process was simplified and enhanced to varying degrees, depending on the individual pilot. The pilots who did utilize the CDTI in their planning felt it was an improvement. None of the pilots stated any negative effect on flight planning as a result of the traffic information.

CDTI self-separation procedures.- Each test crew was required to adapt the CDTI self-separation tasks into their normal procedures. Although basic procedures and suggested guidelines for conducting self-separation were provided the test subjects, crew coordination and implementation tactics were developed by each crew. This resulted in a learning process with some crews developing a workable method quickly and others still experimenting with techniques on their final data run. At the conclusion of the simulation testing, the pilots were asked to rate their confidence in their use of the traffic display for self-separation. As shown in figure 11, there was a wide range of pilot confidence with the self-separation task. In general, the pilots who developed self-separation procedures which conformed closely to their normal flying techniques were most successful and felt more confident with the task.

Workload Considerations

Cockpit workload was assessed in this study by using subjective pilot ratings. The intent of these ratings was to obtain general trends in workload associated with the introduction of traffic display information. Task demand, stress, physical effort, mental effort, achievement, and comfort with the task were the specific workload elements included in this analysis. Postrun questionnaires were used by

each pilot to establish baseline workload ratings for the scenarios flown without CDTI. On subsequent runs of the same scenario, with CDTI added in the monitoring or self-spacing mode, the pilots rated their workload with the baseline ratings used as a reference. The ratings from all the pilots were then analyzed to determine if any discernible trends were evident with the incorporation of the CDTI tasks. The following discussion of results is restricted to the approach scenarios flown in this study.

Figure 12 presents the average ratings for the flying and nonflying pilots for each of the workload elements. A statistical comparison of the CDTI-monitoring and CDTI self-spacing ratings with the baseline ratings is presented in tables III and IV, respectively. The t-value statistic in these tables represents a comparison between the two mean values (no CDTI versus with CDTI) using a pooled standard deviation value with assumed equal population variance (ref. 8). Negative t-values signify an increase in mean rating for the CDTI case; positive t-values indicate a decrease in mean rating with CDTI.

Task demand, stress, physical effort, and mental effort, (figs. 12(a) through (d)) were seen to exhibit the same basic trends. The flying pilots recorded a decrease in ratings (lower workload) for these elements when CDTI was added in the monitoring role, with an increase in rating (higher workload) associated with CDTI self-spacing. The nonflying pilots showed increased ratings for both CDTI monitoring and self-spacing for these same workload elements. The statistical analysis showed a significant increase in task demand and mental effort for the flying pilots when CDTI was used for self-spacing (table IV), with no significant change identified for the CDTI-monitoring case (table III). The nonflying pilot ratings showed significant levels of increase for all four elements with CDTI self-spacing and a significant increase in mental effort with CDTI monitoring.

Pilot achievement and comfort with the task was seen to remain essentially the same for both flying and nonflying pilots (figs. 12(e) and (f)) with CDTI monitoring. The flying pilots did show a decrease in comfort with the task for the CDTI self-spacing mode. The statistical analysis (table IV) showed this decrease in comfort with the task of the flying pilot to be significant.

Pilot comments and observations of crew activities during the simulation runs provided some insight into these workload ratings. As discussed in the section "Cockpit Procedures Considerations," the nonflying pilot was primarily responsible for monitoring instruments and subsystems. The addition of CDTI provided a new system to monitor which resulted in a higher workload for the nonflying pilot. This workload increased most significantly for CDTI self-spacing when the nonflying pilot was required to advise and assist the flying pilot with interpreting the spacing situation as well as monitor and control the display. The flying pilots recorded significant increases in task demand and mental effort when they were required to self-space with the CDTI. The decrease in workload with CDTI monitoring was attributed to the improvement in flight planning information afforded by the CDTI. Since only a few of the pilots utilized the traffic display for planning assistance, the decrease in workload level was not statistically significant. Finally, the decrease in the flying pilot's comfort with the task for CDTI self-spacing was attributed to the lack of confidence and the learning effects experienced by some of the pilots with interpreting and using the display information.

At the conclusion of the simulation runs, the pilots were asked to rate the overall change in cockpit workload associated with using the CDTI for active traffic separation tasks. All the pilots who responded to this question felt CDTI would

result in an acceptable increase in cockpit workload under normal conditions. Most also commented that the workload level would improve with more experience and become even more acceptable. Only a few pilots felt that CDTI self-spacing could be handled solely by the flying pilot. Most agreed that crew coordination was essential to routinely conduct self-spacing. Any situation which required the nonflying pilot to be diverted from the task, such as pressurization problems or other system failures, would probably force cancellation of a self-spacing clearance.

Airport Capacity

Precise control of the in-trail separation intervals of landing aircraft has the potential of increasing arrival capacity of an airport by allowing reduction of the mean separation between aircraft. Previous part-task simulation studies (ref. 5) have shown arrival time accuracies of approximately 8 seconds (1 standard deviation) when the self-spacing technique employed in this study was used. These earlier tests, however, lacked the operational fidelity and full-systems environment believed necessary to obtain realistic spacing results. The spacing performance achieved by the pilots in this study under highly realistic conditions was analyzed for comparison with these previous experiments.

The primary measure of spacing accuracy for in-trail following was the time interval between the lead aircraft crossing a fixed reference point and the trailing aircraft crossing the same point. This time interval, referred to as interarrival time, was equal to 80.0 seconds when the pilots precisely followed the lead aircraft spacing guidance displayed on the CDTI. This value of desired interarrival time was chosen to coincide with the minimum allowable spacing distance permitted by ATC for wake-vortex avoidance at the minimum airspeed flown during the approach. As a result, by following the spacing guidance precisely, the aircraft would be established on final approach at the minimum distance spacing of 3 nautical miles behind the lead aircraft and would cross the runway threshold 80 seconds after the lead aircraft. Without the CDTI guidance, the air traffic controller would issue speed and heading instructions to the aircraft in order to obtain no less than a spacing of 3 nautical miles on final approach.

Figure 13 shows the mean and standard deviation of interarrival time at the outer marker and runway threshold, respectively, for the baseline without CDTI, CDTI-monitoring, and CDTI self-spacing conditions. The initial conditions for all in-trail following runs were the same, with the simulator crew starting 100 seconds behind the lead aircraft. The profile flown by the lead aircraft was also the same for all conditions. Although these results do not reflect a mix of aircraft profiles or initial separation conditions, interesting observations and comparisons between controller spacing and pilot self-spacing can be made.

The best final spacing performance at runway threshold was achieved when the pilots performed the CDTI self-spacing task. Mean interarrival time was reduced from 89.4 seconds without CDTI to 82.2 seconds with CDTI self-spacing. In addition, the dispersion in arrival times was reduced from a standard deviation of 16.6 seconds without CDTI to 10.0 seconds with self-spacing. This result compares favorably with the standard deviation of 8 seconds arrival accuracy reported in reference 5.

The conditions where CDTI was used for monitoring, with the controller providing separation, were found to result in a degradation of spacing performance. The mean interarrival time for the CDTI-monitoring runs increased by nearly 15 seconds over the baseline, with an accompanying increase of 9 seconds in the standard deviation.

The reason for this increase was not readily apparent from either pilot comments or recorded flight parameters. Cockpit video tapes of the CDTI-monitoring runs, however, showed several of the pilots watching the traffic as they flew the approach and adjusting their speeds and turn rates slightly to insure separation from the traffic. These actions resulted in larger spacing intervals behind the lead aircraft than were seen during the no-CDTI runs. Since the CDTI-monitoring conditions were the first runs each crew made with the traffic display in a realistic traffic pattern, at least some of the degradation in spacing performance was most likely due to learning effects.

These results suggest that traffic displays may produce undesirable effects on the ATC system during the initial stages of CDTI introduction. Pilots do appear to react to the traffic situations with slight alterations in their flight profiles and tend to be more conservative in their maneuvering through a traffic pattern when first exposed to CDTI. Without adequate training and experience with the traffic display, this conservative tendency could result in increased spacing intervals and decreased airport capacity. With an active spacing task and proper guidance, however, pilots could achieve accurate spacing performance which exceeds that provided by the air traffic controller. The close agreement of the spacing performance achieved by the test subjects in this study with that of the part-task study in reference 5 suggests that effects of aircraft mix and initial spacing error could be evaluated with simpler part-task simulations. Without such analyses, the overall benefit to airport capacity afforded by CDTI self-spacing cannot be accurately assessed.

Aircraft Fuel Efficiency

The addition of CDTI and, in particular, the new tasks involving CDTI self-spacing can affect the aircraft operating efficiency by modifying the flight profile of the CDTI-equipped aircraft. Further, the techniques employed by each pilot to adapt to the CDTI tasks can affect the overall efficiency of the flight. Although these issues were not specifically addressed in this study, the comparative performance results obtained with and without CDTI in these simulation tests may provide some insight in this area.

The approach scenario flown in this study was representative of present-day operations into Denver. The pilots were given profile descent clearances from cruise altitude with restrictions necessary for control sector hand-off and coordination. Typical speed restrictions were applied in the terminal area with a nominal path distance flown for the runway configuration and ILS approach being executed. The time of arrival was essentially fixed since each approach followed the same lead aircraft with the same required spacing interval. Variations in aircraft operating efficiency were therefore a sole function of pilot technique in flying the approach and the resultant fuel usage.

A comparison of distance flown and fuel burned from the start of the scenario to the outer marker of the landing runway for the no-CDTI, CDTI-monitoring, and CDTI self-spacing conditions are shown in figure 14. The two cases where the air traffic controller provided separation (no CDTI and CDTI monitoring) were seen to have the same distance flown, with the CDTI self-spacing case having a noticeably shorter distance. The no-CDTI condition had the lowest fuel usage, with CDTI self-spacing indicating a large increase in both mean and standard deviation of fuel burned. The increase in fuel used for the CDTI-monitoring cases was attributed to the longer

flight times associated with these runs as discussed in the section "Airport Capacity."

The shorter distance flown for the CDTI self-spacing conditions was a result of the difference between the controller's spacing technique and that of the CDTI spacing guidance. The CDTI self-spacing technique directed the pilot to remain a fixed time interval behind the lead aircraft and follow the same ground track. The controller was not restricted to a specific in-trail spacing interval or ground track. He would use speed, heading, and altitude commands to maintain separation, with a final goal of a spacing of 3 nautical miles on final approach. Typically, the controller allowed the aircraft to reduce spacing on the lead aircraft on the downwind leg of the approach to a closer interval than that used by the CDTI spacing technique. By delaying the base turn slightly, the controller could then achieve the desired final spacing without excessive speed control on the aircraft. As a result, the controller-spaced runs exhibited longer path lengths than the CDTI-spaced runs.

The greater fuel usage for the CDTI self-spacing conditions was found to be a result of the initial conditions which placed the simulator 100 seconds behind the lead aircraft, with a desired spacing of 80 seconds. This 20-second error placed the own-aircraft symbol behind the spacing box on the display indicating the need to fly faster. As a result, the pilots would maintain some power during the descent in order to catch the spacing box. This situation, as mentioned by several of the pilots, was an unnecessary "fine-tuning" of the spacing at a point in the approach where spacing was not critical. As the lead aircraft approached the airport it would naturally be slowing down. The pilots could then catch the spacing box at some point after the lead aircraft began slowing down without burning extra fuel during the initial descent. The wide variation in fuel used for the CDTI self-spacing conditions was a direct result of the degree to which the pilots tried to catch the spacing box early during the descent. In all cases, the fuel burn could have been as low as the no-CDTI case if the capture of the spacing box had been delayed.

These results point out the need for two major considerations when using CDTI self-spacing. First, a specific spacing clearance should not be given too early during an approach where speed control and precise spacing are not necessary. Second, spacing guidance should exhibit adequate buffers in order to allow maximum flexibility in the efficient operation of the aircraft.

ATC Impact

CDTI provides the crew of an aircraft with a detailed electronic view of traffic previously limited to the radar displays of air traffic controllers. This information provides the possibility of expanded pilot participation in the aircraft separation process, as explored in the CDTI self-separation tasks in this study. Interaction and coordination between pilots and controllers are primary areas of concern for successful implementation and utilization of cockpit traffic displays. Candidate procedures for use of CDTI for flight operations during IMC were developed for this study. These procedures included CDTI self-spacing clearances between controllers and pilots. The impact of these procedures on air traffic control in this study provides some insight into possible operational effects of CDTI on the air traffic control process.

The primary link between pilots and air traffic control is through voice radio communication. An important measure of CDTI impact is in the change in communication loading afforded by the presence and use of cockpit traffic displays. During each

simulation run in this study, radio activity was monitored through audio and digital data recordings of cockpit microphone usage. These data were analyzed in terms of the number of unique communications which occurred during each run and the average time for each communication. This analysis was limited to the cockpit activity associated with ATC communications and did not include the controller radio times. The controller would have the same number of communications as the aircraft; however, the controller time per communication was not recorded.

Figure 15 shows results of the communication analysis for the approach scenarios with no CDTI, CDTI monitoring, and CDTI self-spacing. The average number of approach communications was reduced by approximately one (4 percent) with CDTI monitoring and by approximately three (12 percent) with CDTI self-spacing compared with the no-CDTI baseline. Pilot average time per communication decreased by approximately 0.2 second with CDTI monitoring and increased by approximately 0.2 second with CDTI self-spacing. These results illustrate two major points. First, CDTI in a monitoring role did not invoke additional pilot communications with ATC. Throughout all simulation runs with CDTI, none of the test subjects questioned ATC concerning traffic on the display. The pilots were able to resolve any questions they had about the traffic by using the display data tag and predictor features and by listening to the ATC partyline communications with the traffic. Second, the in-trail spacing procedures developed for this study resulted in a measurable decrease in communication loading. This decrease in communication loading was a result of the elimination of the speed and heading vectors normally given to the aircraft when the controller provided in-trail separation. This result implies the possibility of increasing traffic capacity without increasing communication loading by the incorporation of CDTI self-spacing procedures. The overall workload of the air traffic controllers, however, must be considered before CDTI self-spacing could be implemented. In addition, multiple CDTI-equipped aircraft performing self-spacing would decrease the normal ATC partyline communications which might prompt questioning of controllers by the pilots.

The results of the communication analysis for the departure scenarios are presented in figure 16. An increase in both the number of communications (approximately 25 percent) and the average time per communication (approximately 12 percent longer) was recorded for the departures when CDTI self-separation was employed. The major problem associated with these operations was the coordination between controller and pilot in identifying the conflicting traffic. This coordination resulted in excessive communication loading being required in order to carry out the self-separation task. It should be noted that the communication loading was a direct result of the procedures developed for this study. Further study is necessary to evaluate procedures which would minimize traffic identification and coordination problems associated with departures in a highly dynamic traffic environment. Most likely, procedures would be required for each departure routing which would be established prior to takeoff and understood by departure and approach controllers as well as the pilots flying the departures and CDTI-equipped approach aircraft.

SUMMARY OF RESULTS

A simulation study was conducted to evaluate flight operations using cockpit display of traffic information in a conventional jet transport aircraft during instrument meteorological conditions. The following results are based on this study:

1. The addition of traffic information in the cockpit was well received by the airline flight crews in this study. Monitoring and operation of the traffic display

was routinely handled by the nonflying pilot. CDTI self-separation tasks required the flying pilot to modify his primary instrument scan to include the traffic display, which was located above the throttle quadrant. Pilot comments stressed the importance of consistent procedures and crew coordination for utilizing the display effectively.

2. Distraction from other cockpit duties was found to be a potential problem with cockpit traffic displays. The compelling nature of the device and the novelty of the electronic display in an otherwise conventional electromechanical cockpit were cited by the test subjects as reasons for this distraction. Additional experience and exposure to the CDTI should lessen the distraction potential. Display formats developed for self-separation tasks may require primary airspeed and altitude warnings to alert the pilots to situations requiring attention to primary flight instrumentation.

3. Pilot workload was found to increase when given a self-separation task to perform with the CDTI. All test subjects indicated these workload levels to be acceptable during the simulation tests. CDTI-monitoring tasks resulted in slightly higher workload for the nonflying pilot compared with no CDTI although less than that recorded for the self-spacing cases. The flying pilots reported a decrease in workload with CDTI monitoring resulting from the improved flight planning available with the CDTI information. All pilots stressed the need for operational experience with CDTI in order to adequately assess the impact on workload.

4. The pilots in this study achieved spacing performance at the runway threshold of a mean interarrival time of 82.2 seconds with a standard deviation of 10.0 seconds when using CDTI approach in-trail self-spacing with a desired interarrival time of 80.0 seconds. The same approach scenarios flown without CDTI resulted in mean interarrival time of 89.4 seconds with a standard deviation of 16.6 seconds. These results suggest the possibility of increased airport capacity with the use of CDTI self-spacing by reducing arrival time dispersion at the runway.

5. Several pilots in this study exhibited a tendency to be more conservative in maneuvering the aircraft through a traffic pattern when first exposed to CDTI without an active spacing task to perform. This conservative tendency resulted in larger spacing intervals at the runway threshold when the pilots had the CDTI for monitoring than when no CDTI was viewed in the cockpit. This result was attributed to the lack of experience and training on the CDTI prior to the monitoring simulation runs. Operational use of a traffic display must be carefully introduced with adequate training to avoid degradation in airport capacities resulting from pilot-induced separation increases.

6. The approach self-spacing clearances and spacing guidance used in this study were found to result in additional fuel consumption compared with the same scenarios without self-spacing. The issuance of spacing clearances early in the descent with an initial 20-second spacing error, combined with a too restrictive buffer of 15 seconds on the spacing display, were identified as the cause of the additional fuel consumption. Operational self-spacing clearances must be designed to allow maximum flexibility during the early stages of descent in order to avoid wasting fuel. Display guidance should also allow variable spacing buffers in order to accommodate fuel-efficient procedures during noncritical phases of the approach.

7. CDTI in a monitoring role did not increase the ATC radio communication loading for the approach scenarios. The in-trail self-spacing scenarios showed a decrease of approximately 12 percent in the average number of ATC communications

compared with the same scenarios flown without CDTI. This decrease in communication loading was a result of the elimination of the speed and heading vectors normally given to the aircraft when the controller provided in-trail separation.

8. The departure self-separation procedures evaluated in this study produced a 25-percent increase in ATC communications compared with no-CDTI baseline departures. The problem of identifying and confirming specific traffic to be avoided by the flight crew was the cause of the excessive communications. Revised procedures which do not require detailed coordination between pilots and controllers for each specific traffic aircraft would be necessary to provide a workable system for departure self-separation.

NASA Langley Research Center
Hampton, VA 23665-5225
February 12, 1986

APPENDIX A

PILOT BRIEFING INSTRUCTIONS

Denver Southwest Approach

Description.- This scenario represents the final segments of a flight into Denver Stapleton International Airport. The scenario begins with your aircraft in cruise prior to initiating descent and ends when you cross the runway threshold. The information you need to fly this approach is contained in this write-up or will be transmitted to you by Air Traffic Control (ATC).

Initial Conditions.- Your aircraft is in cruise flight crossing the ELBEC intersection at flight level 330 and a speed of .76 Mach. Your VHF NAV 1 is tuned to Gunnison VORTAC (114.9), and you are flying the 046 deg radial from Gunnison (jet route J10). VHF NAV 2 is tuned to Denver VORTAC (117.0) in preparation for intercept of the 213 deg radial toward Denver. VHF Comm should be tuned to Denver Center (133.52) for ATC communication.

Specific Ground Rules

1. Prior to starting the simulation run, check that all instruments and switches are set properly for cruise.
2. Your task is to fly the final cruise, descent and approach to landing segments of a flight into Denver Stapleton International Airport.
3. ATC communications will be provided, and you are required to observe proper protocol and carry out the ATC instructions as in actual practice. Your call sign is NASA 599.
4. Plan on a landing weight of 95000 lb.
5. Winds aloft are negligible in this scenario.
6. Initial descent should be started prior to the the ACREE waypoint. A descent speed schedule of approximately 300 KIAS should be flown until reaching the profile descent crossing points or instructed otherwise by ATC.
7. Normal operating procedures as described in your airline procedures manual should be observed. This includes mandatory call out of checklist items.
8. Limitations on landing gear and flap extension speeds should be strictly observed.
9. Crew duties may be assigned as the Captain deems appropriate as long as they conform to normal operating procedures.
10. Every effort should be made to fly the aircraft in a manner which you feel would be acceptable for airline operations.
11. Since visual scene is not presented in this simulator, level off at decision height (200 ft) and continue to fly at approach speed. The simulator will go to RESET when you cross the runway threshold.

Denver South Departure

Description.- This scenario represents a south departure from Denver Stapleton International Airport following a takeoff to the north. The scenario begins on the runway before takeoff and ends when you are clear of the terminal area. Engine start and pre-takeoff items are not simulated and are not required. Takeoff performance is also not simulated faithfully; however, it is necessary to conduct the takeoff in order to initiate the scenario. Please note that excessive column deflection and force is required for takeoff rotation.

Initial conditions.- Your aircraft is on the ground ready for takeoff on runway 35L at Denver Stapleton International Airport. Contact ATC on 127.6 when ready for your departure clearance. Your outbound radial from Denver VOR will be 185. The simulator will be placed in OPERATE when you receive takeoff clearance.

Specific Ground Rules

1. Prior to starting the simulation run, check that all instruments and switches are set properly for takeoff.
2. Your task is to fly a departure from Denver Stapleton International Airport. The scenario will end when you are outbound on the Denver 185 deg radial and clear of the Denver terminal area.
3. ATC communications will be provided, and you are required to observe proper protocol and carry out the ATC instructions as in actual practice. Your call sign is NASA 599.
4. Takeoff weight is 96000 lb.
5. Normal operating procedures and all aircraft operational limitations should be observed.
6. Crew duties may be assigned as the Captain deems appropriate.
7. Every effort should be made to fly the aircraft in a manner which you feel would be acceptable for airline operations.

APPENDIX B

CDTI SELF-SEPARATION PROCEDURES

PROCEDURES FOR USE OF COCKPIT DISPLAY
OF TRAFFIC INFORMATION (CDTI)

DISPLAY SEPARATION

- A. Display separation is a method employed by ATC to separate aircraft by instructing a pilot to avoid or follow another aircraft by means of information from a CDTI.
- B. When it will be operationally beneficial, ATC may authorize an aircraft equipped with an operating CDTI to
 - (1) Provide his own in-trail separation behind a preceding aircraft of similar performance. This separation interval will be specified in a time parameter (seconds) and the pilot is expected to maintain the spacing within plus or minus 15 seconds.
 - (2) Provide his own lateral separation from another aircraft during climb or descent according to the following separation standards:
 - (a) FL 290 or above - 2000 feet vertical separation until separated by three or more miles laterally (SIX miles if the other aircraft is a heavy jet).
 - (b) Below FL 290 - 1000 feet vertical separation until separated by three or more miles laterally (SIX miles if the other aircraft is a heavy jet).

EXAMPLE:

Once the pilot has reported having identified the correct preceding or crossing aircraft on his CDTI:

MAINTAIN (number) SECONDS IN TRAIL OF (preceding traffic's identification), (if appropriate) UNTIL (specified time, fix, or altitude).

or

MAINTAIN DISPLAY SEPARATION FROM (traffic's identification), CLIMB/DESCEND AND MAINTAIN (altitude).

- C. When a pilot has been instructed to provide display separation, he/she should promptly notify the controller if the other aircraft is no longer displayed or if the pilot cannot accept the responsibility for the separation for any reason.
- D. In cases not involving in-trail following, the controller shall advise the second aircraft of the intentions of the first aircraft.

EXAMPLE:

TRAFFIC (number) O'CLOCK, (number) MILES (direction) BOUND, HAS YOU COCKPIT IDENTIFIED, WILL MAINTAIN DISPLAY SEPARATION AND CLIMB/DESCEND THROUGH YOUR ALTITUDE.

- E. A pilot's acceptance of instructions to provide display separation from heavy jet aircraft is also an acknowledgement that the pilot accepts the responsibility for wake turbulence separation.

NOTE: Minimum longitudinal wake turbulence separation is six nautical miles when in trail of a heavy jet aircraft.

- F. Pilots should remember that the availability of a CDTI does not preclude their regulatory responsibility (FAR 91.67(a)) to see and avoid other aircraft when weather conditions permit.

DISPLAY APPROACH

- A. When it will be operationally beneficial, ATC may authorize an aircraft to conduct an ILS or MLS approach to an airport while maintaining a separation interval behind a preceding aircraft as specified in the approach clearance. This self-separation task may only be conducted by aircraft equipped with an operating CDTI.
- B. Display approaches are initiated by ATC to expedite traffic and reduce controller workload by allowing the pilot to share the separation responsibility. It is the pilot's responsibility to advise ATC as soon as possible if a display approach is not desired or cannot be continued.
- C. Controllers may authorize a display approach provided:
 - (1) The aircraft's CDTI is operational and the pilot agrees.
 - (2) The preceding aircraft has been positively identified on the pilot's CDTI.
 - (3) Approved separation is applied between aircraft so cleared and between these aircraft and other IFR or special VFR aircraft.

EXAMPLE:

Once the pilot has reported having identified the correct preceding aircraft:

MAINTAIN (number) SECONDS IN TRAIL OF (preceding traffic's identification) (restrictions as appropriate), CLEARED FOR ILS/MLS RUNWAY (number) DISPLAY APPROACH

- D. Acceptance of a display approach clearance to follow a preceding aircraft is pilot acknowledgement that he will maintain the prescribed separation interval (plus or minus 15 seconds) behind the preceding aircraft until crossing the final approach fix. The pilot is then also responsible for maintaining at least the minimum wake turbulence separation throughout the remainder of the approach until the preceding aircraft crosses the landing threshold.

NOTE: Minimum longitudinal wake turbulence separation is six nautical miles when in trail of a heavy jet aircraft.

- E. After being cleared for a display approach, the pilot shall proceed via a similar ground track as the preceding aircraft - while complying with all ATC and charted altitude restrictions and separation requirements - to the ILS/MLS approach in use.
- F. A display approach, because it uses ILS or MLS guidance, is an IAP. Therefore, if a go around is necessary for any reason, aircraft will be expected to execute the missed approach procedure as published on the applicable ILS/MLS approach chart.
- G. The controller shall
 - (1) Issue a display approach clearance to appropriately equipped aircraft when the pilot reports having positively identified the aircraft which is to be followed.
 - (2) Continue flight following and traffic advisories until the aircraft is instructed to contact the tower.
 - (3) Inform the pilot conducting the display approach of the aircraft class when pertinent traffic is known to be a heavy aircraft.

CDTI Pre-Brief Items

- 1. Purpose of the study is to evaluate impact of CDTI on cockpit workload and procedures. Display format and specific CDTI procedures are not the main topics of the study; however, comments and suggestions for improvements will be solicited for these items.
- 2. CDTI display and self-separation procedures are candidate concepts only and do not represent any current FAA plans.
- 3. TCAS used to display traffic is a fairly accurate model of Bendix enhanced TCAS II currently under development. Major differences in our model:
 - all traffic within range of the sensor are displayed.
 - proximity, threat, and resolution advisory aircraft will be displayed as flashing symbols of appropriate color. No aural alarm or TCAS computed resolution maneuver will be given.
 - lead aircraft in self-spacing will automatically be tracked by TCAS, regardless of threat status.
- 4. CDTI/touchpanel display is a research system and has not been refined for operational use.
 - response time of touchpanel is slower than desired.
 - display software has not been developed and refined to properly

- display software has not been developed and refined to properly handle TCAS initialization and dropout characteristics. Large transients in target positions, groundspeeds, and predictor vectors may occur from time to time.

5. CDTI self-separation requires proper interpretation of display information.

- own and target predictor vectors indicate potential horizontal conflicts. Maneuver to prevent target from entering your 3 n.mi. airspace if altitude clearance is not possible.
- matching own predictor length with speed reference arc will maintain proper in-trail spacing.
- groundspeed of lead aircraft is not reliable while the aircraft is turning.
- in-trail spacing will require some speed brake/throttle in order to maintain proper speeds. Do not rely on pitch to control airspeed.

APPENDIX C

TEST QUESTIONNAIRES

Pilot's Questionnaire

Pilot:

Date:

Please circle your answer to the following questions:

1. How did using the traffic display for aircraft separation affect your workload compared to the flights where separation was provided by ATC?

unacceptable increase in workload	acceptable increase in workload	no effect on workload	small decrease in workload	large decrease in workload
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2. How likely do you feel it is that a cockpit traffic display would cause a distraction from necessary cockpit duties?

very likely	likely	moderately likely	not likely
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3. How confident do you feel about your understanding and ability to use the traffic display effectively and safely for maintaining separation?

not very confident	slightly confident	somewhat confident	acceptably confident	very confident
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4. Do you feel that the system as used in this simulation will result in a more safe or less safe operation with respect to collision avoidance?

much less safe	somewhat less safe	no change in safety	somewhat more safe	much more safe
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5. Was the simulation adequately realistic for the purposes of this experiment?

very unrealistic	somewhat unrealistic	somewhat realistic	acceptable realism	very realistic
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6. Based on your flying experience and your participation in this experiment, list the benefits and limitations of a cockpit traffic display in general, and the use of the display for maintaining separation from other aircraft.

Provide any comments or suggestions you may have in regard to the following:

7. The traffic display format and information.

8. The touchpanel operation.

9. The CDTI self-separation procedures.

10. The experiment in general.

Post-Flight Questionnaire

Condition number:

Pilot:

1. Indicate your rating of the cockpit workload associated with the previous flight.

	(Low)					(High)				
Task demands	1	2	3	4	5	6	7	8	9	10
Stress	1	2	3	4	5	6	7	8	9	10
Physical effort	1	2	3	4	5	6	7	8	9	10
Mental effort	1	2	3	4	5	6	7	8	9	10
Achievement	1	2	3	4	5	6	7	8	9	10
Comfort w/task	1	2	3	4	5	6	7	8	9	10

2. How confident were you in the traffic situation on the previous flight?
(not confident) 1 2 3 4 5 6 7 8 9 10 (very confident)

3. Comments:

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TABLE I.- TRAINING AND TEST RUN SEQUENCE

[Pilot debriefings and workload ratings
were conducted after each data run,
actual duration of events varied
between crews]

Event (a)	Activity	CDTI level	Duration, hr
1	Simulator familiarization		3.0
2	CDTI familiarization		2.0
3	CDTI self-spacing practice		2.0
4	Condition 1 approach data run	No CDTI	0.5
5	Condition 2 approach data run	CDTI monitoring	0.5
6	Condition 3 approach data run	CDTI self-spacing	0.5
7	Condition 4 departure data run	No CDTI	0.2
8	Condition 5 departure data run	CDTI self-separation	0.2
9	Condition 3 repeat	CDTI self-spacing	0.5
10	Condition 1 repeat	No CDTI	0.5
11	Debriefing		1.0

^aEvents 1 through 3 were conducted on first day; events 4 through 11 on second day.

TABLE II.- TEST MATRIX

Test condition	Crew number							
	1	2	3	4	5	6	7	8
Practice ^a	^b x	x	x	x	x	-	-	x
1	x	-	-	x	x	x	x	x
2	x	x	x	x	x	x	x	x
3	x	x	x	x	x	x	x	x
4	x	x	x	x	x	x	x	x
5	x	x	x	x	x	x	x	x
3 repeat	x	x	x	x	x	x	x	x
1 repeat	x	-	x	x	x	x	x	x

^aPractice run was condition 1 without traffic.

^bIndicates completed run.

TABLE III.- PILOT WORKLOAD RATINGS FOR CDTI MONITORING

Workload measure	No CDTI		CDTI monitoring		t-value
	Mean	Standard deviation	Mean	Standard deviation	
Flying pilot					
Task demand	3.58	1.44	3.00	1.22	0.952
Stress	3.23	1.25	2.75	1.20	0.880
Physical effort	3.46	1.39	3.00	1.22	0.779
Mental effort	3.65	1.49	3.25	1.48	0.614
Achievement	7.08	1.49	7.50	1.58	-0.628
Comfort with task	7.46	1.12	7.50	1.58	-0.067
Traffic confidence	7.35	1.38	8.63	0.99	^a -2.295
Nonflying pilot					
Task demand	3.00	1.20	3.75	1.09	-1.456
Stress	2.54	0.55	3.00	1.22	-1.223
Physical effort	2.77	0.50	3.25	1.09	-1.428
Mental effort	2.85	0.70	4.13	1.17	^b -3.244
Achievement	7.15	0.36	7.38	1.73	-0.470
Comfort with task	7.15	1.66	7.50	1.50	-0.487
Traffic confidence	6.92	1.66	8.00	1.32	-1.569

^a5-percent significance level.

^b1-percent significance level.

TABLE IV.- PILOT WORKLOAD RATINGS FOR CDTI SELF-SPACING

Workload measure	No CDTI		CDTI self-spacing		t-value
	Mean	Standard deviation	Mean	Standard deviation	
Flying pilot					
Task demand	3.58	1.44	4.91	1.87	^a -2.155
Stress	3.23	1.25	4.13	1.65	-1.651
Physical effort	3.46	1.39	4.16	1.78	-1.176
Mental effort	3.65	1.49	4.91	1.80	^a -2.056
Achievement	7.08	1.49	7.16	1.34	-0.150
Comfort with task	7.46	1.12	6.50	1.80	^a 1.722
Traffic confidence	7.35	1.38	8.00	1.22	-2.376
Nonflying pilot					
Task demand	3.00	1.20	4.25	1.20	^b -2.849
Stress	2.54	0.55	3.44	1.06	^b -2.849
Physical effort	2.77	0.50	3.50	0.94	^b -2.613
Mental effort	2.85	0.70	4.44	1.17	^b -4.439
Achievement	7.15	0.36	7.69	1.20	-1.602
Comfort with task	7.15	1.66	7.19	1.42	-0.487
Traffic confidence	6.92	1.66	8.06	1.20	^a -2.178

^a5-percent significance level.

^b1-percent significance level.

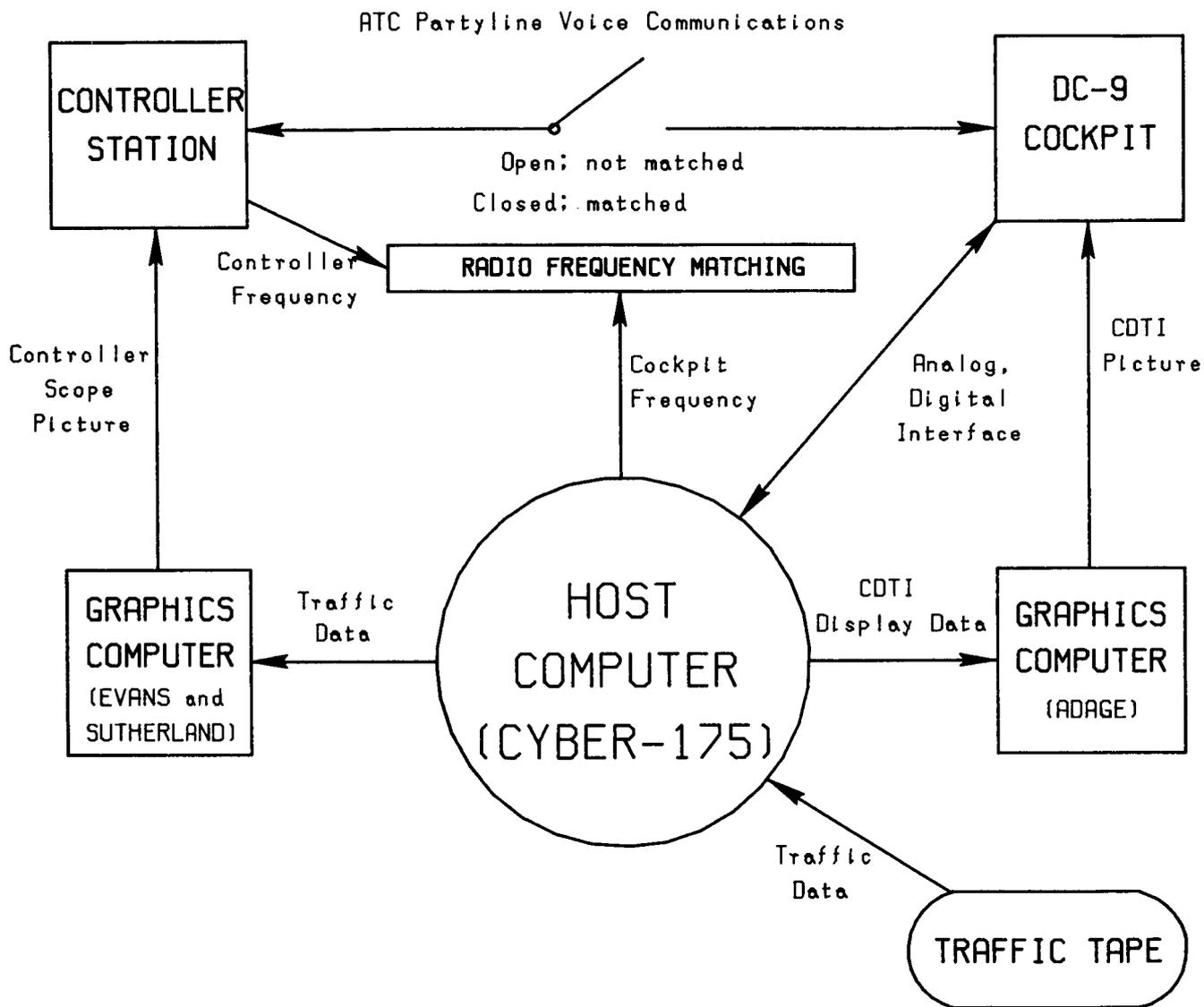


Figure 1.- Block diagram of research system.

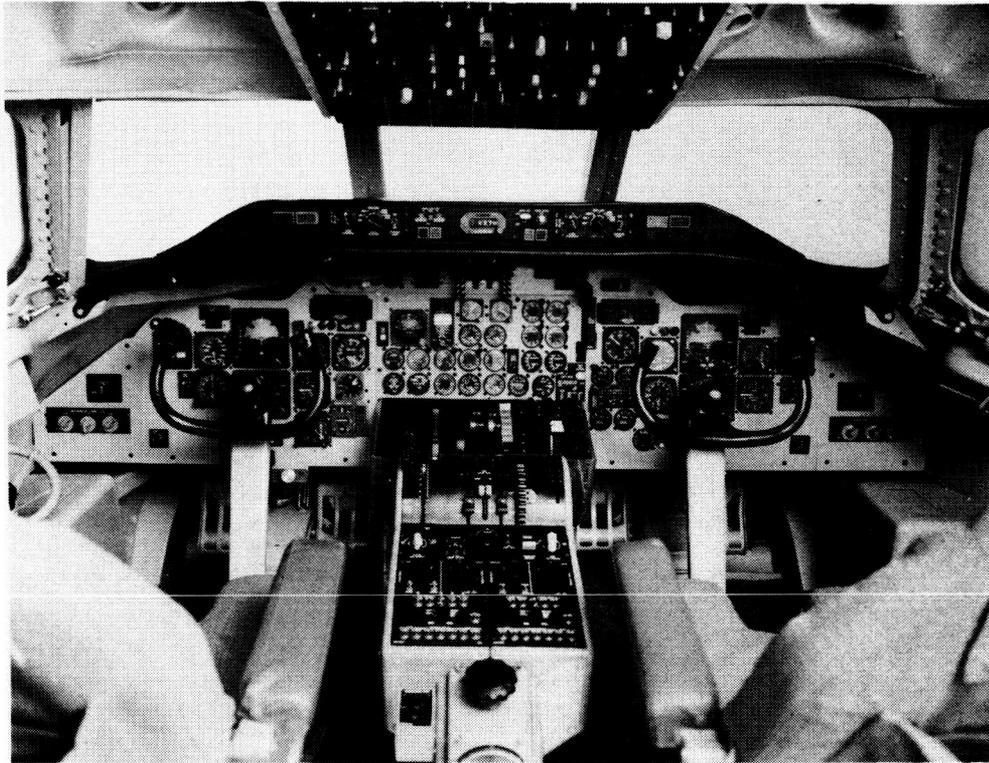


Figure 2.- DC-9 cockpit simulator. L-82-10,572

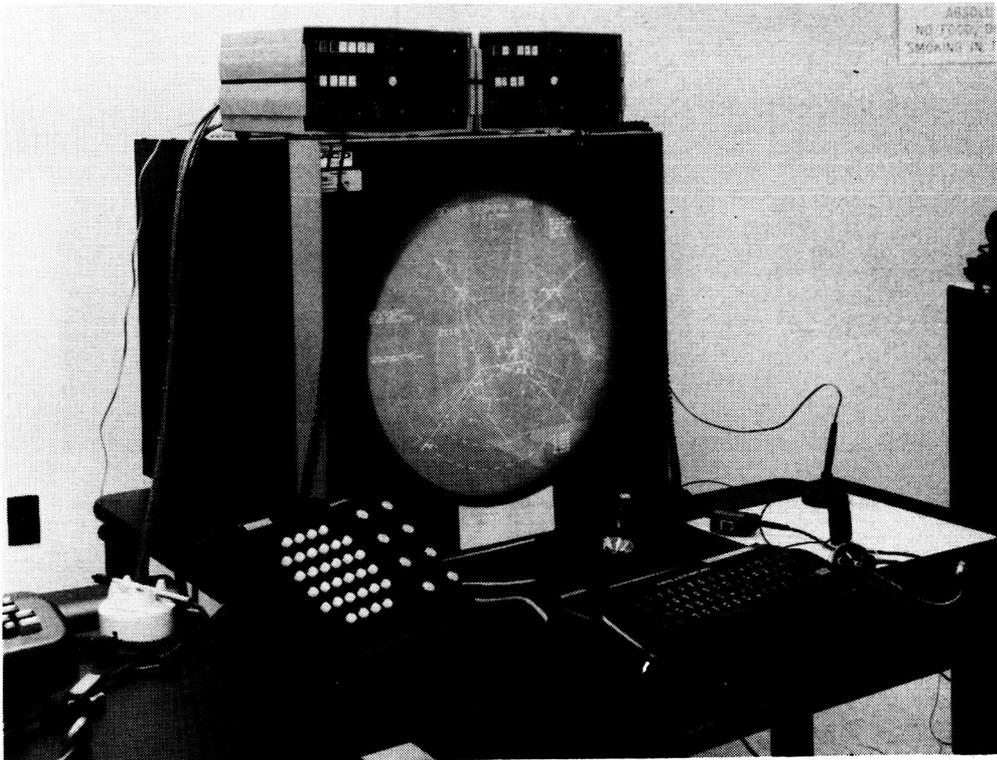


Figure 3.- Air traffic control station. L-83-7,832

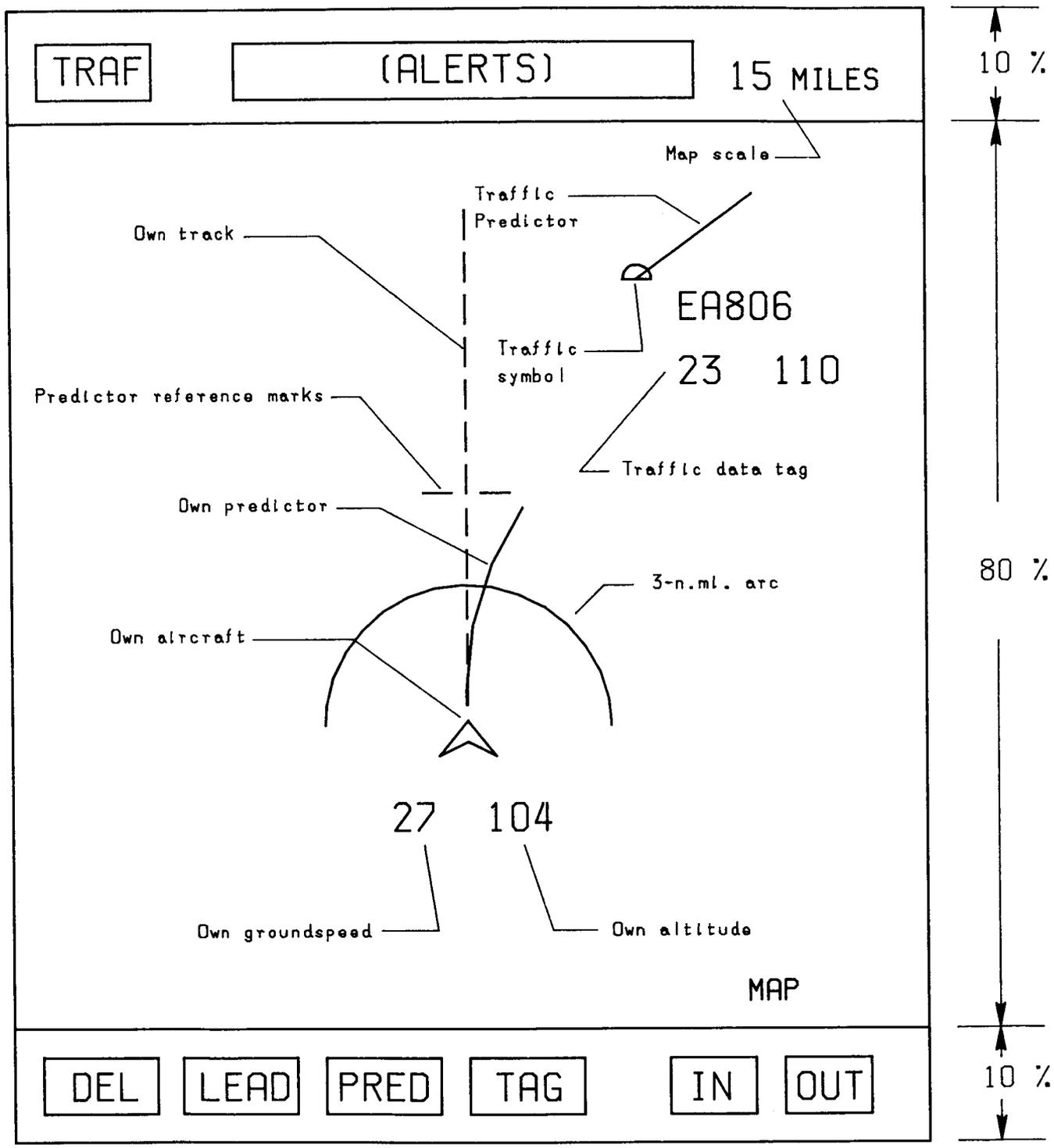


Figure 4.- CDTI display format.

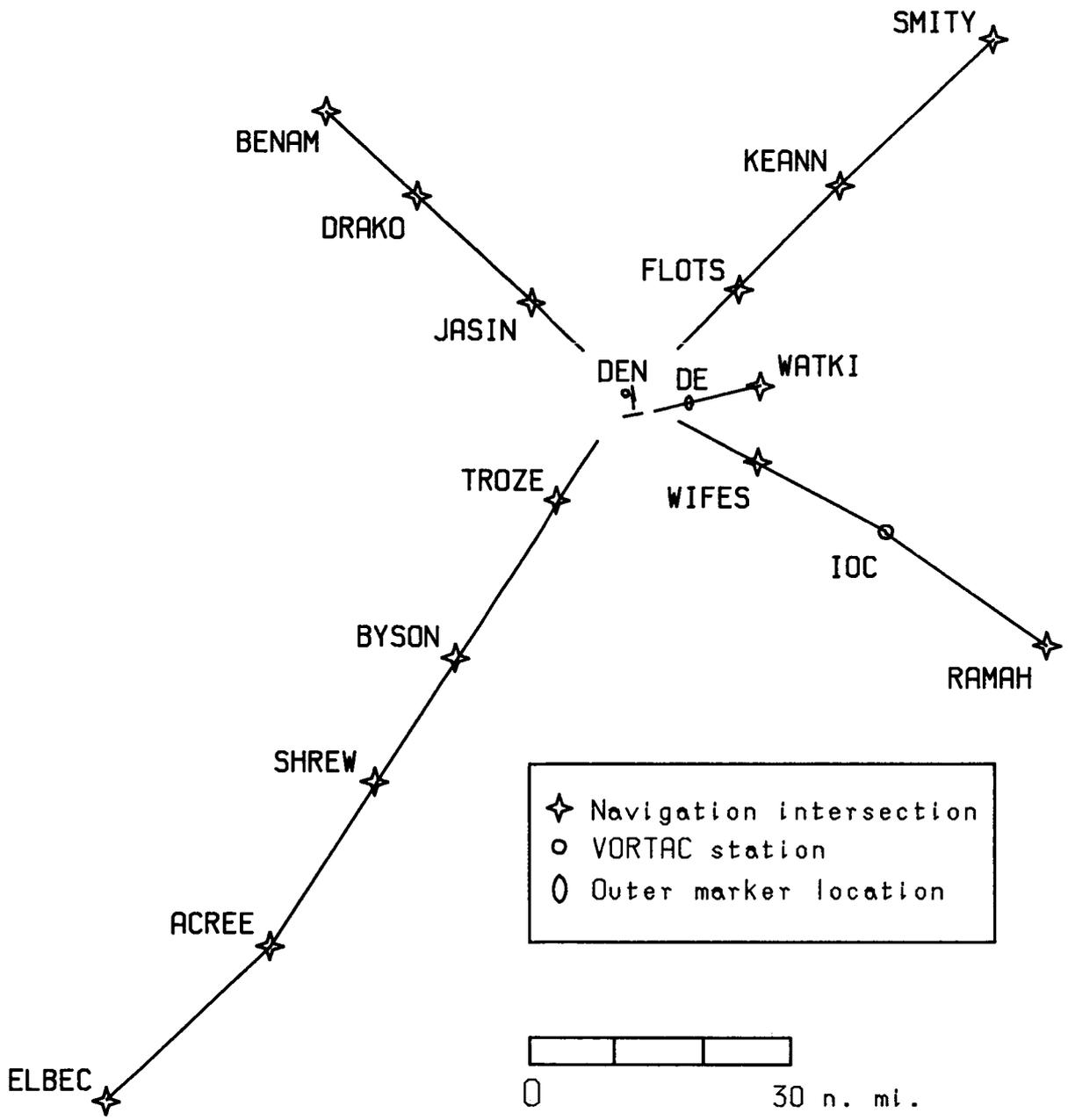


Figure 5.- Map display format.

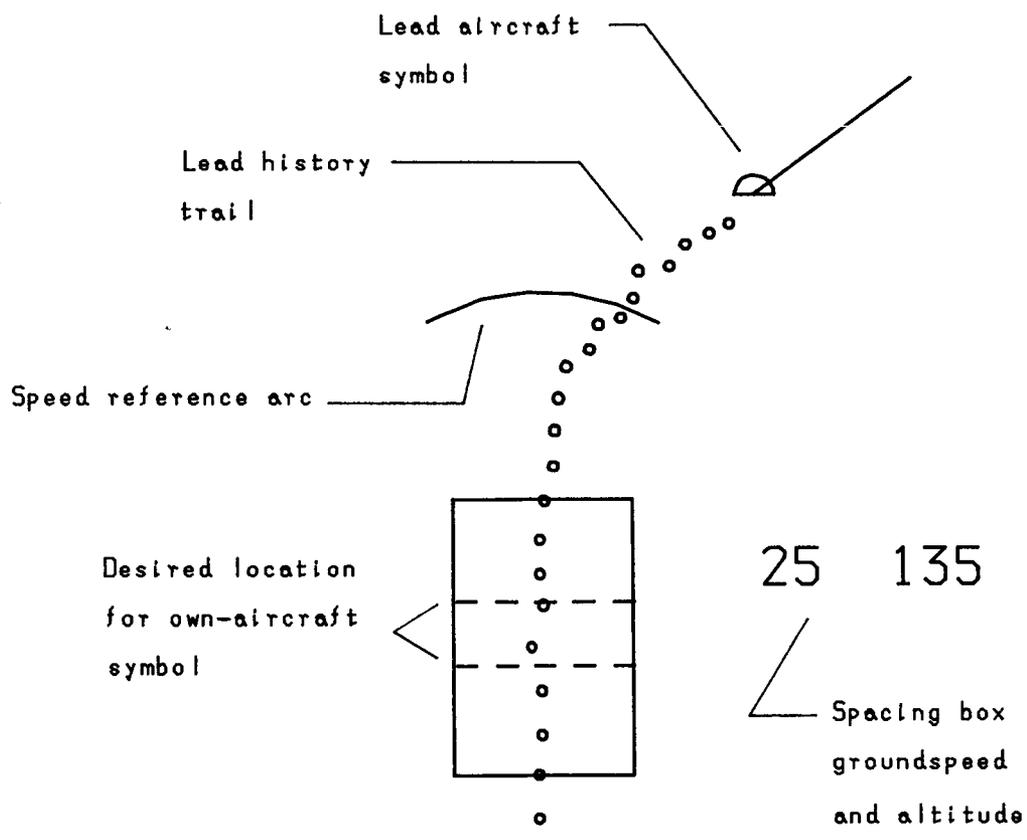
ALTITUDE	TCAS TRACKING STATUS	
	TRACKED	NOT TRACKED
within 500 ft of own altitude	○	*
500 ft or more above own altitude	◐	✱
500 ft or more below own altitude	◑	✴

Figure 6.- Traffic symbology.

TRAF

[Empty box]

15 MILES



MAP

DEL

LEAD

PRED

TAG

IN

OUT

Figure 7.- Lead aircraft spacing information.

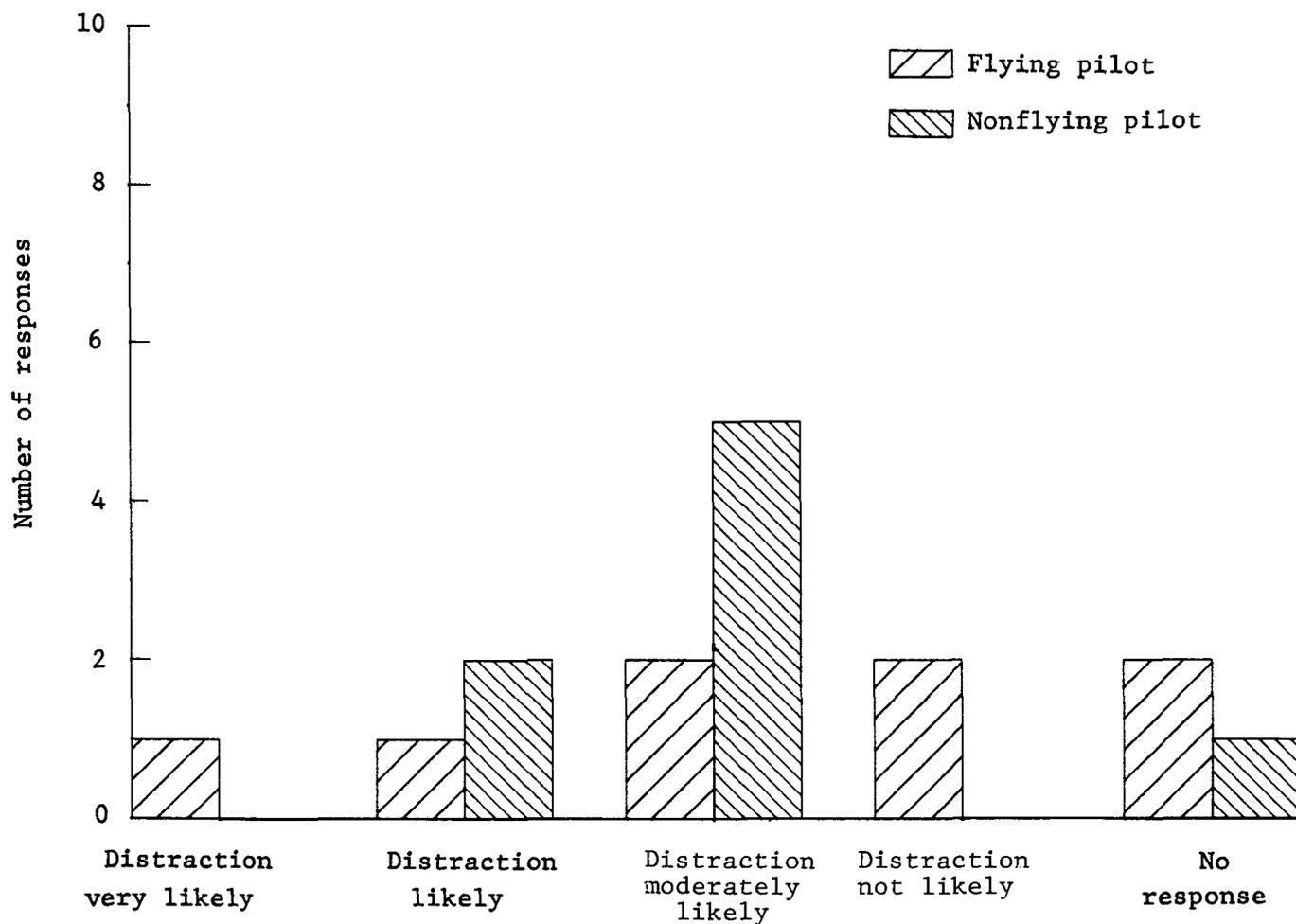


Figure 8.- Pilot rating of CDTI distraction from normal cockpit duties.

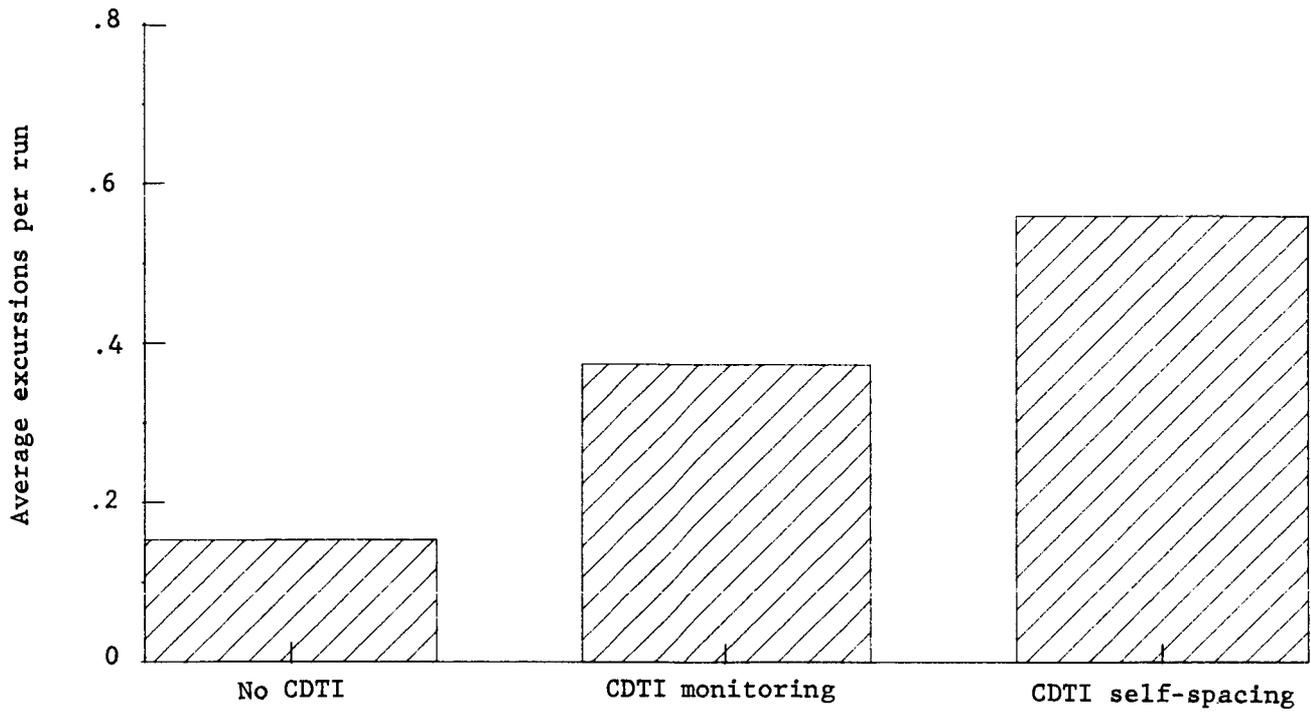


Figure 9.- Frequency of airspeed excursions.

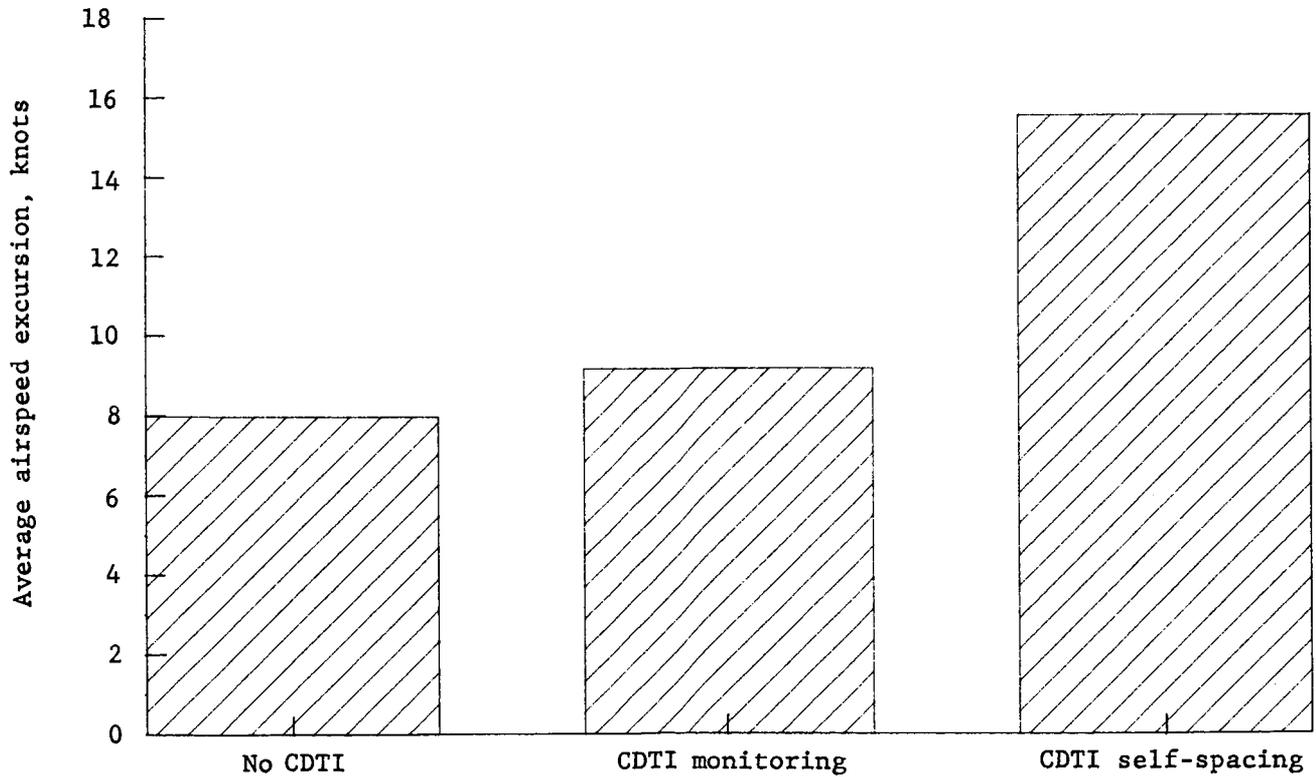


Figure 10.- Magnitude of airspeed excursions.

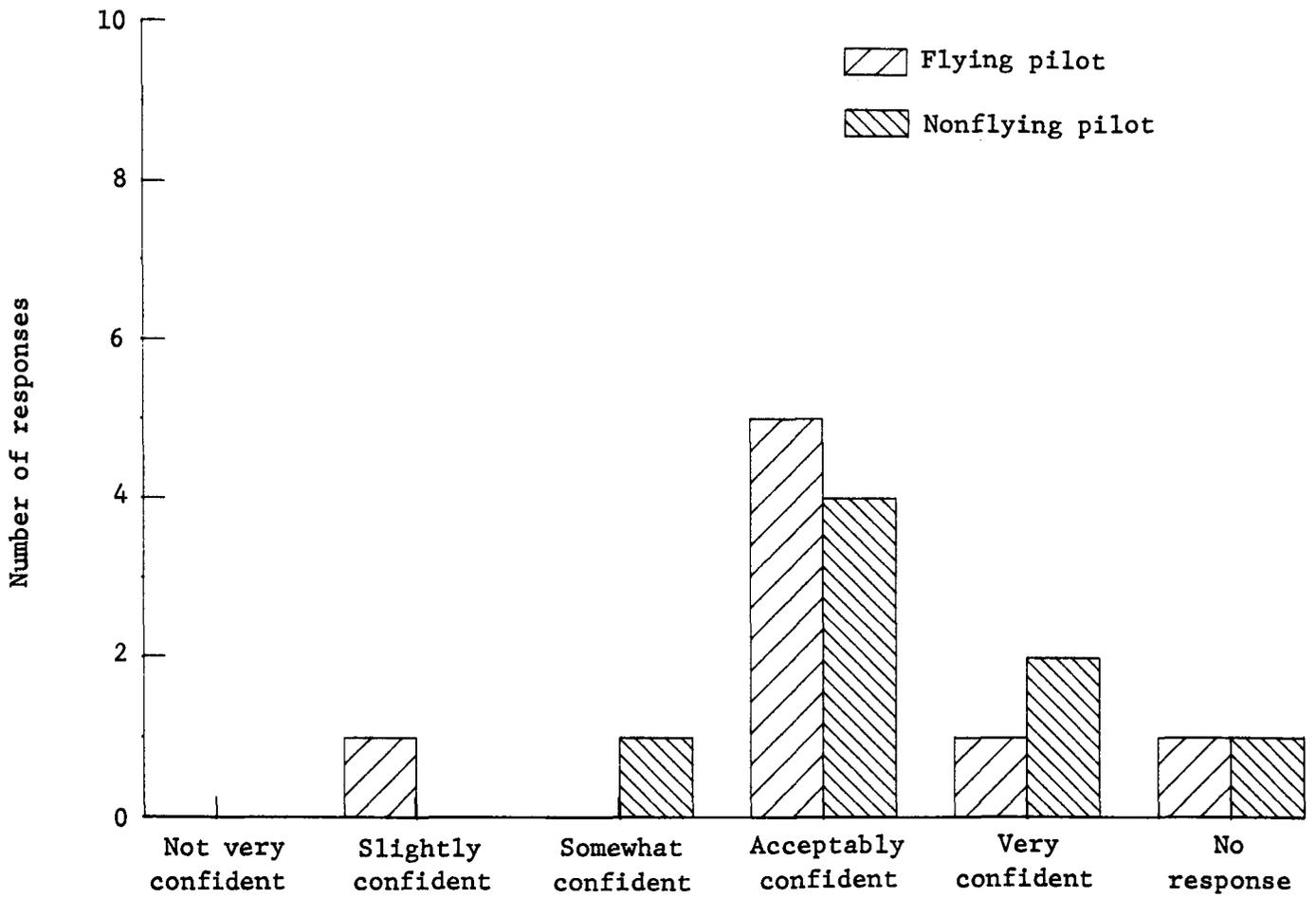
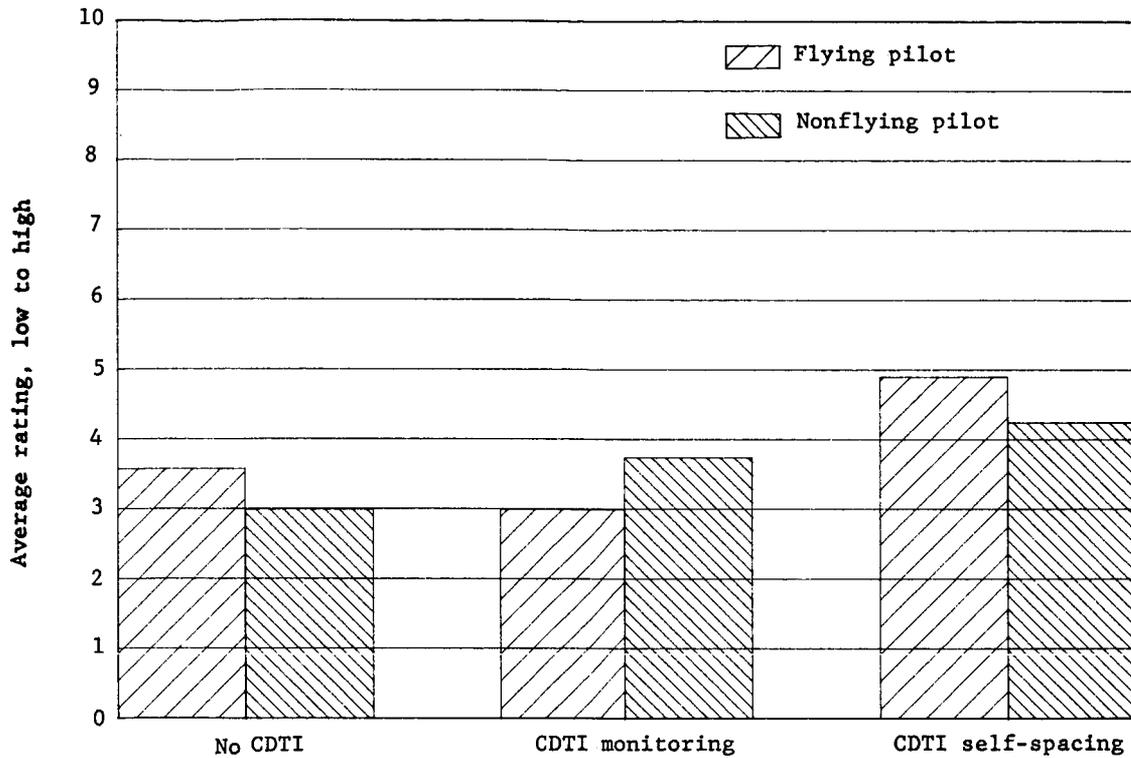
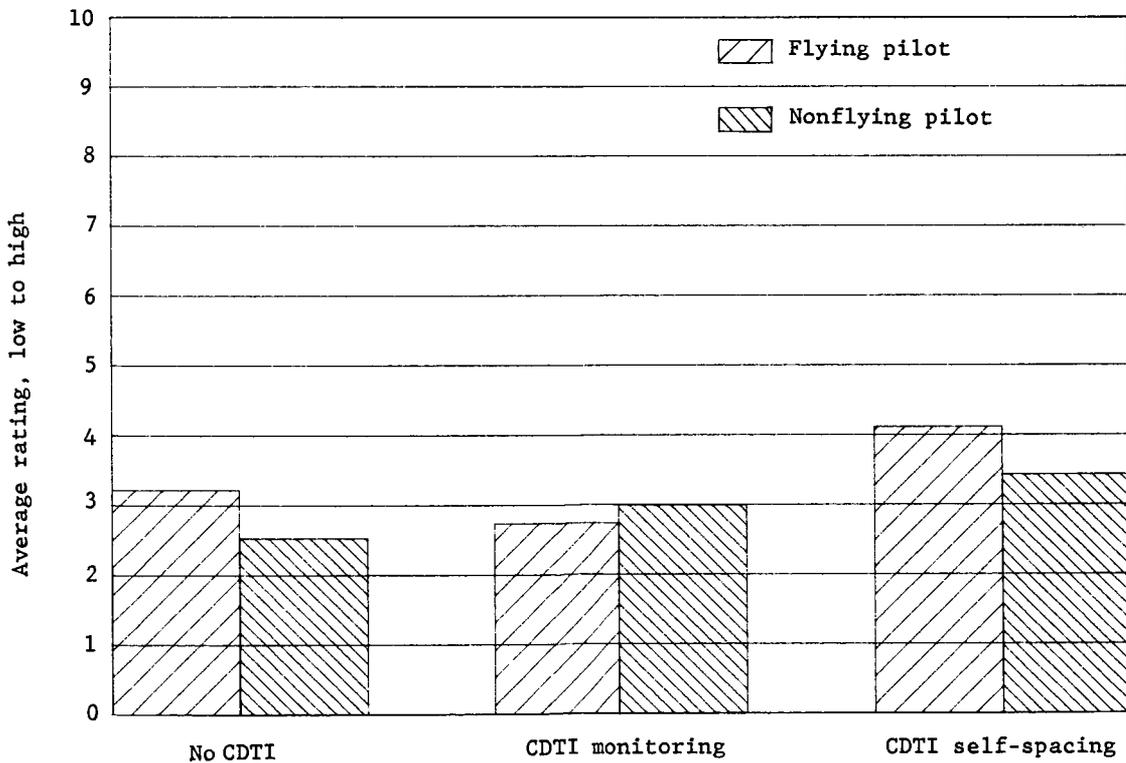


Figure 11.- Pilot rating of confidence with using CDTI for self-spacing.

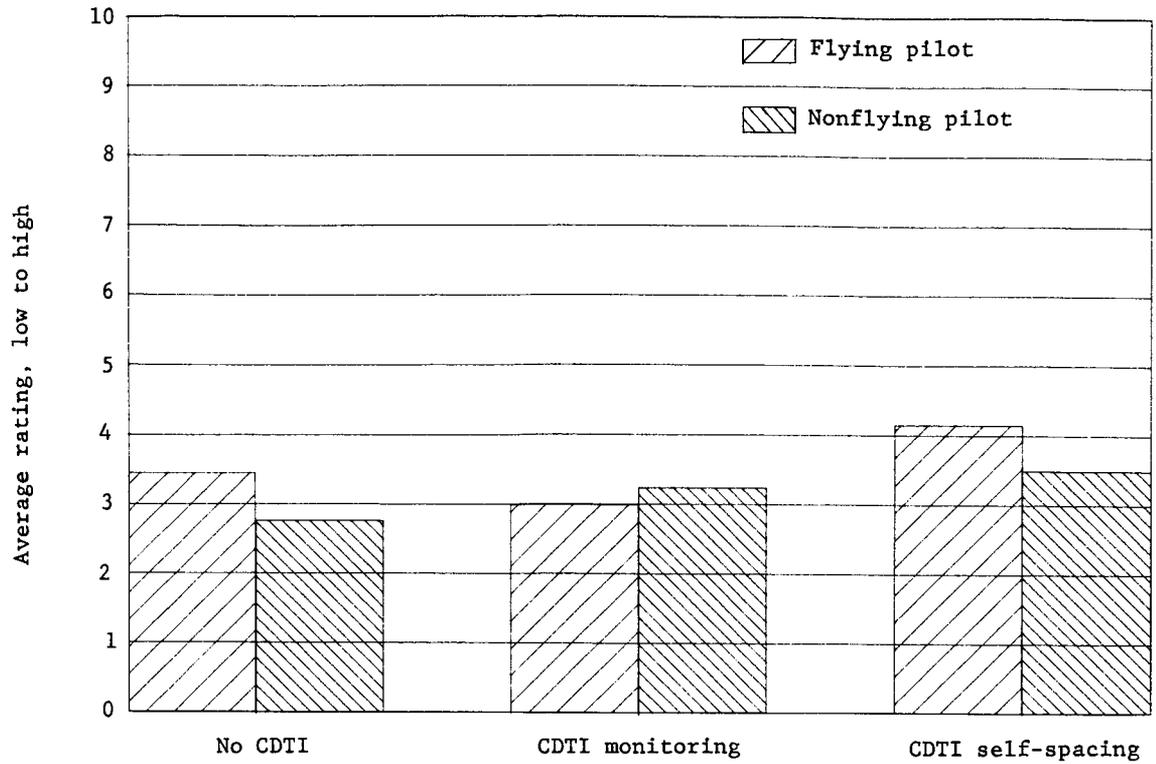


(a) Task demand.

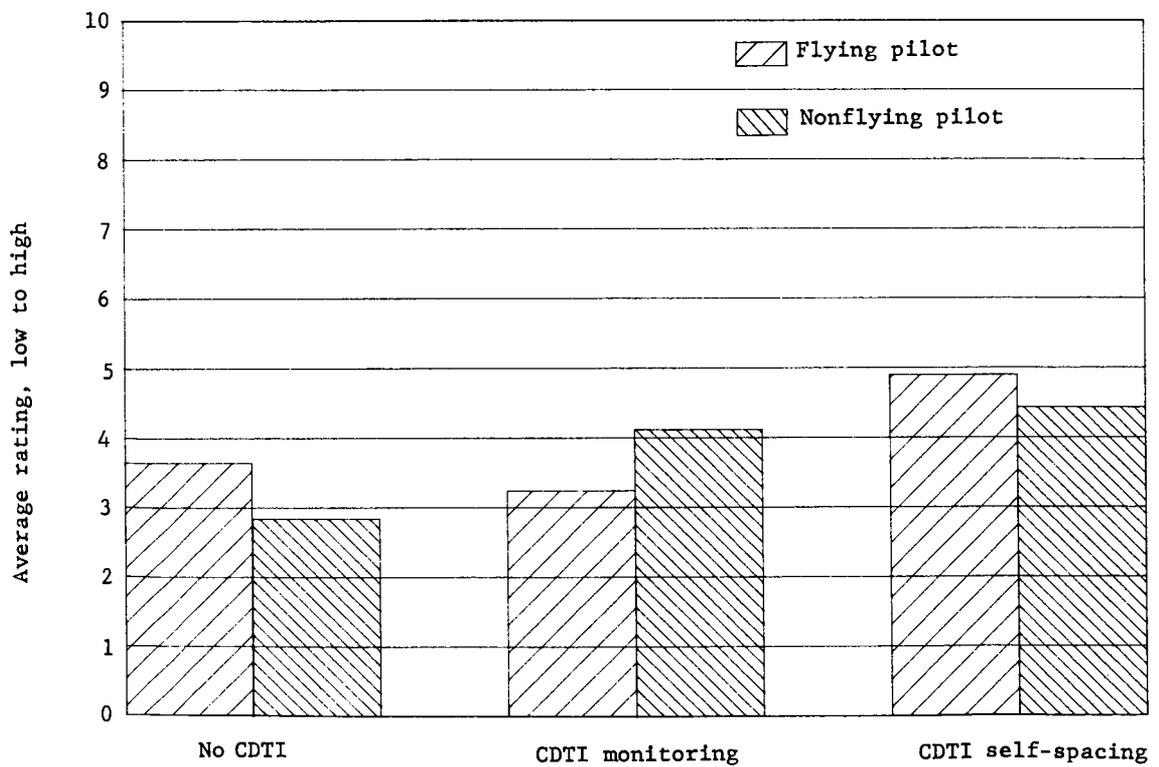


(b) Stress.

Figure 12.- Pilot ratings of workload during approach scenarios.

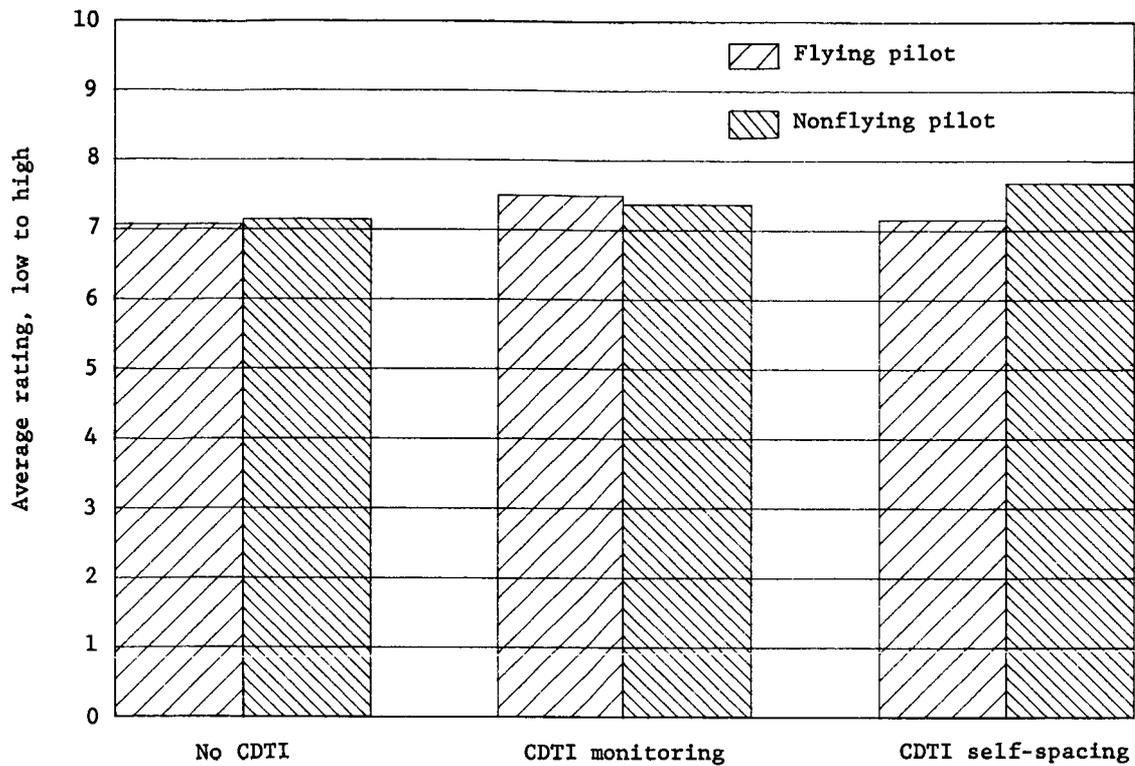


(c) Physical effort.

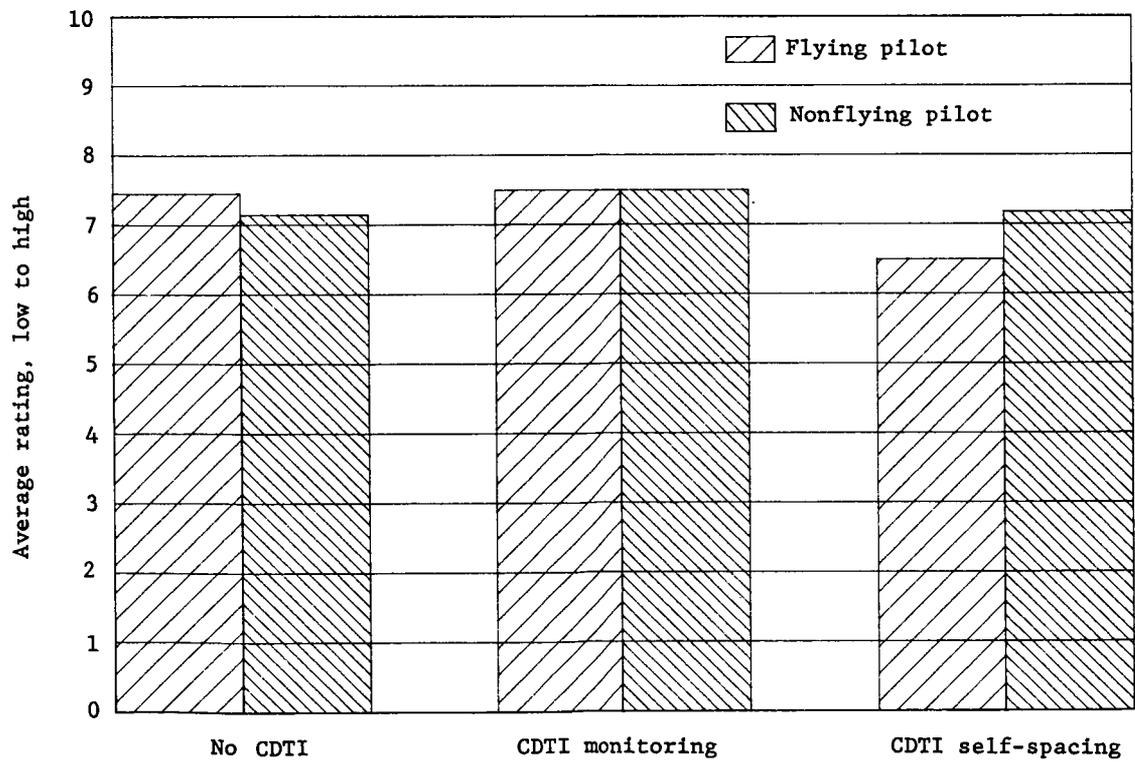


(d) Mental effort.

Figure 12.- Continued.

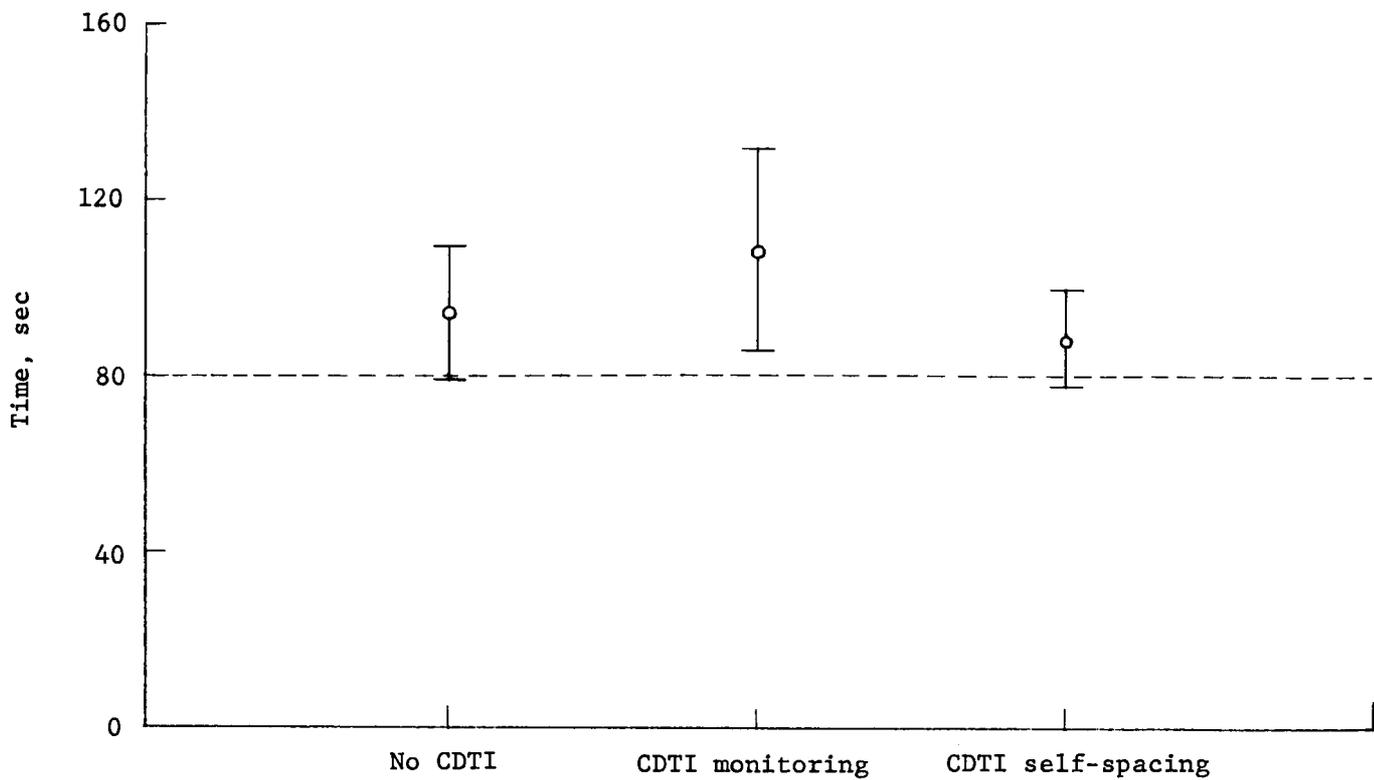


(e) Task achievement.

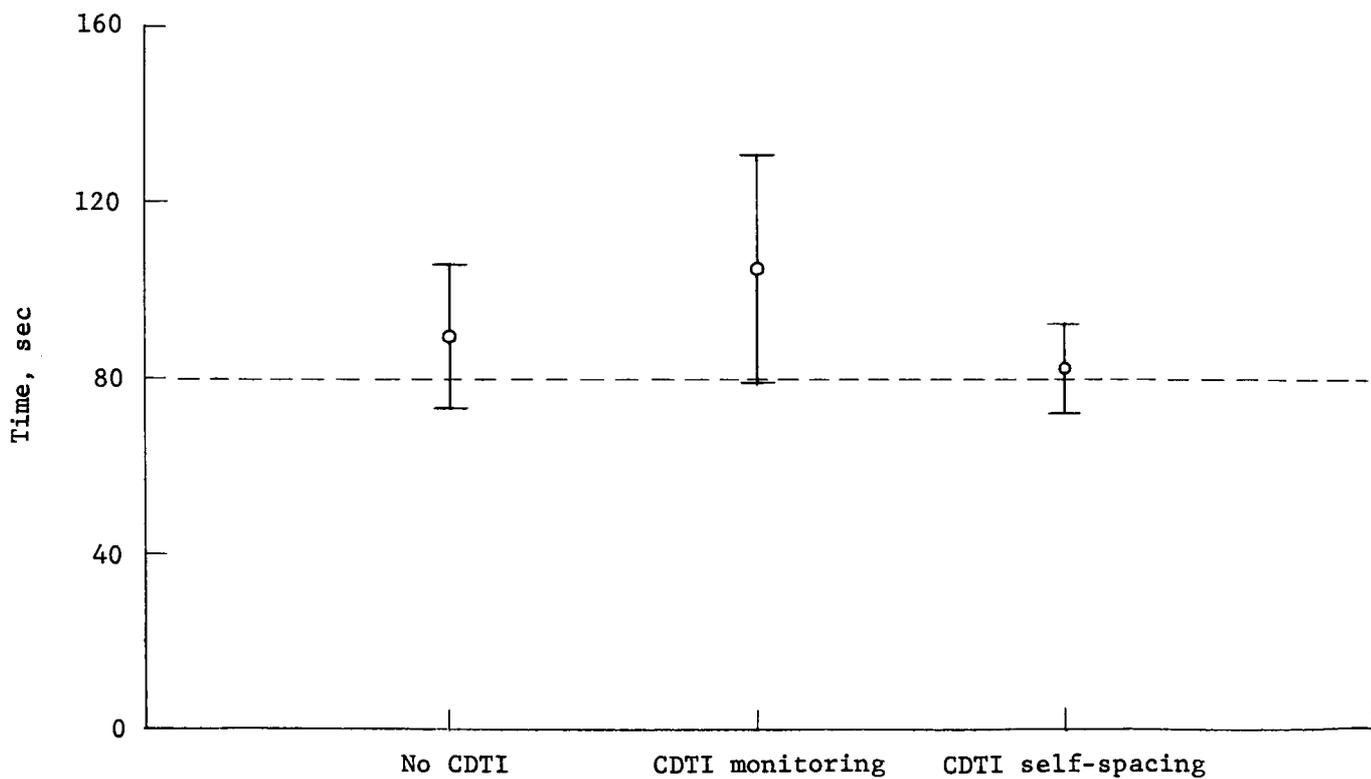


(f) Comfort with task.

Figure 12. Concluded.

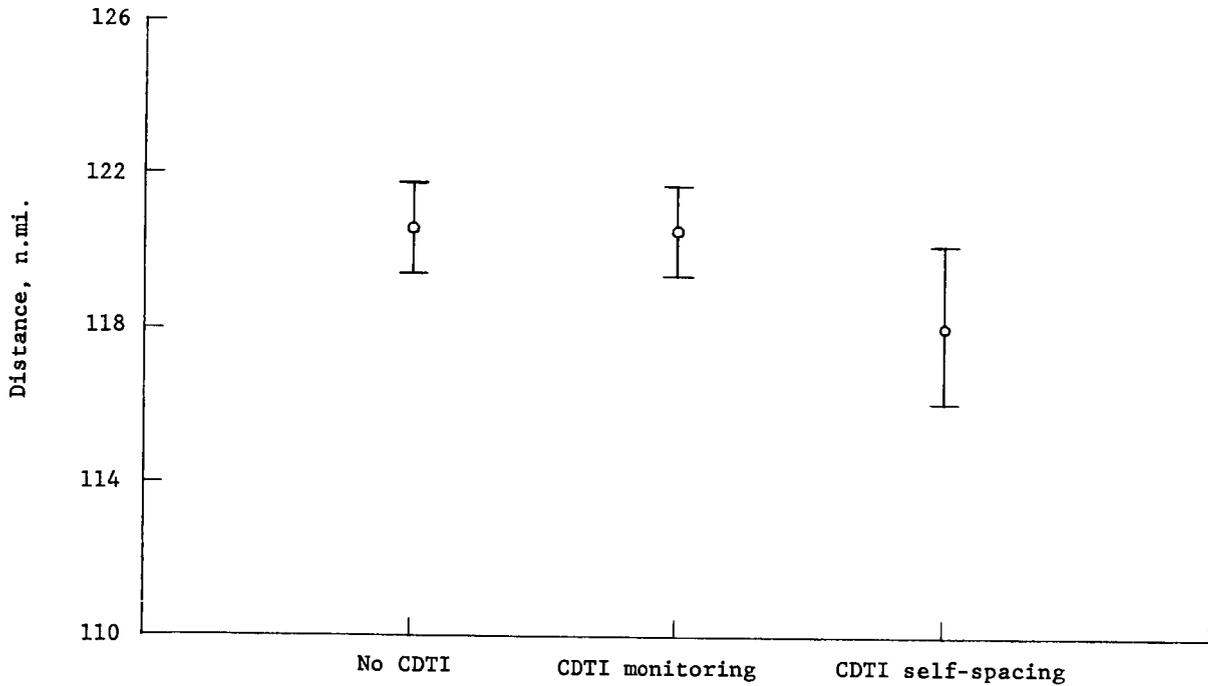


(a) Outer marker.

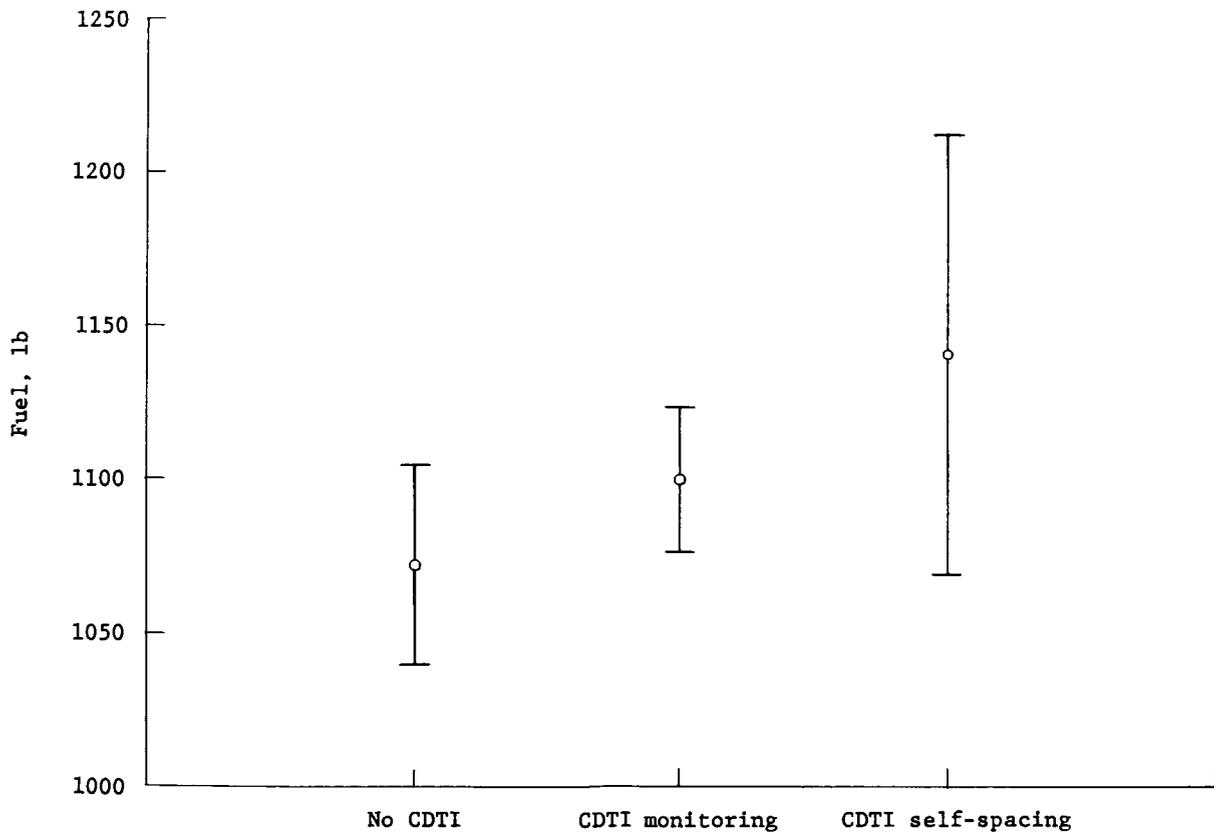


(b) Runway threshold.

Figure 13.- Interarrival times for approach scenarios.

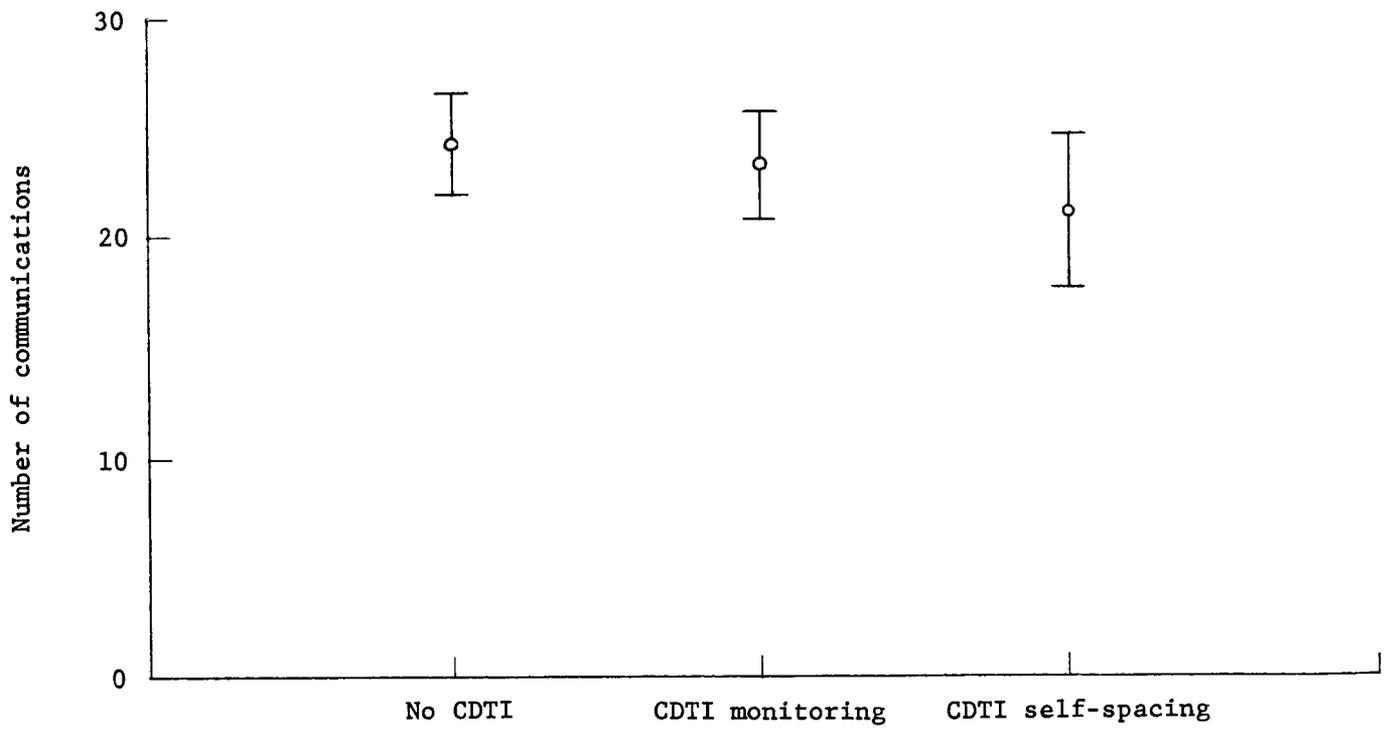


(a) Distance flown.

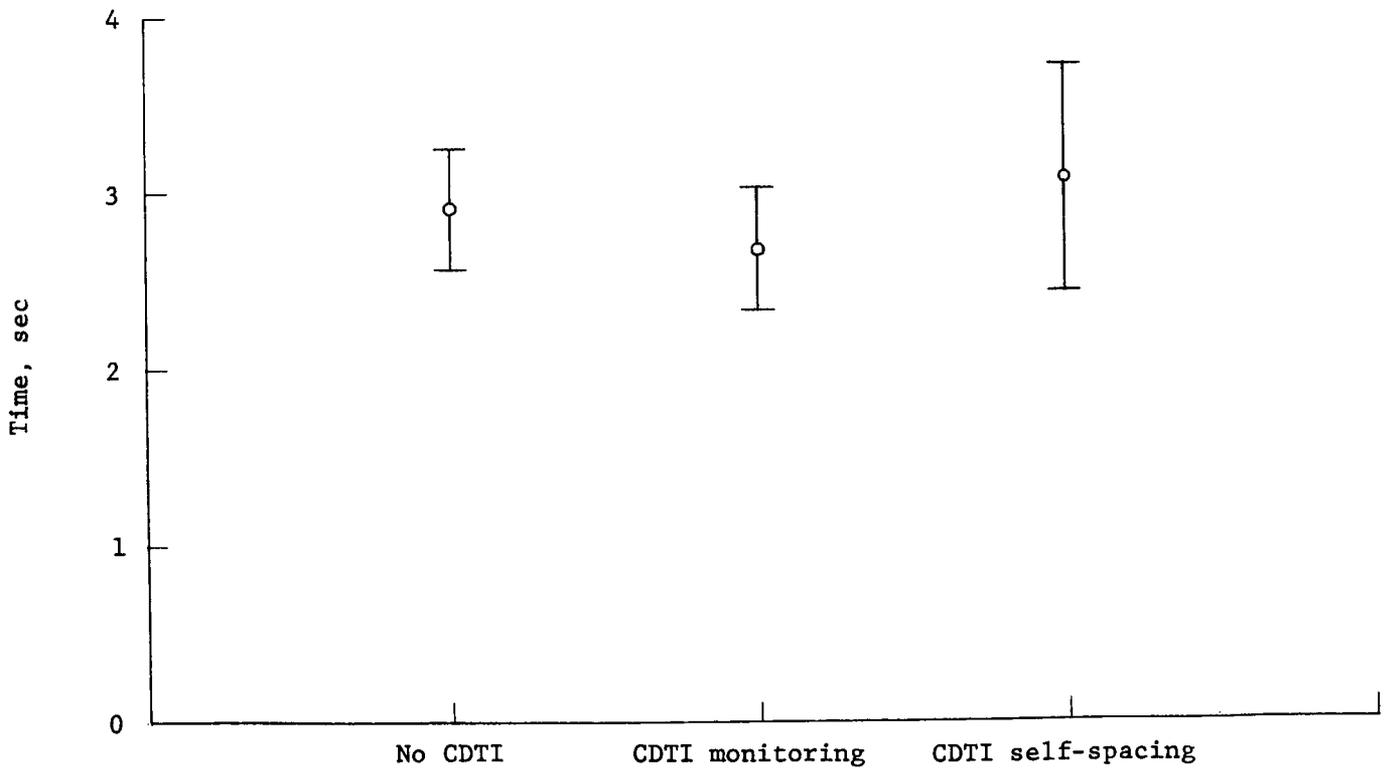


(b) Fuel used.

Figure 14.- Airplane efficiency at outer marker for approach scenarios.

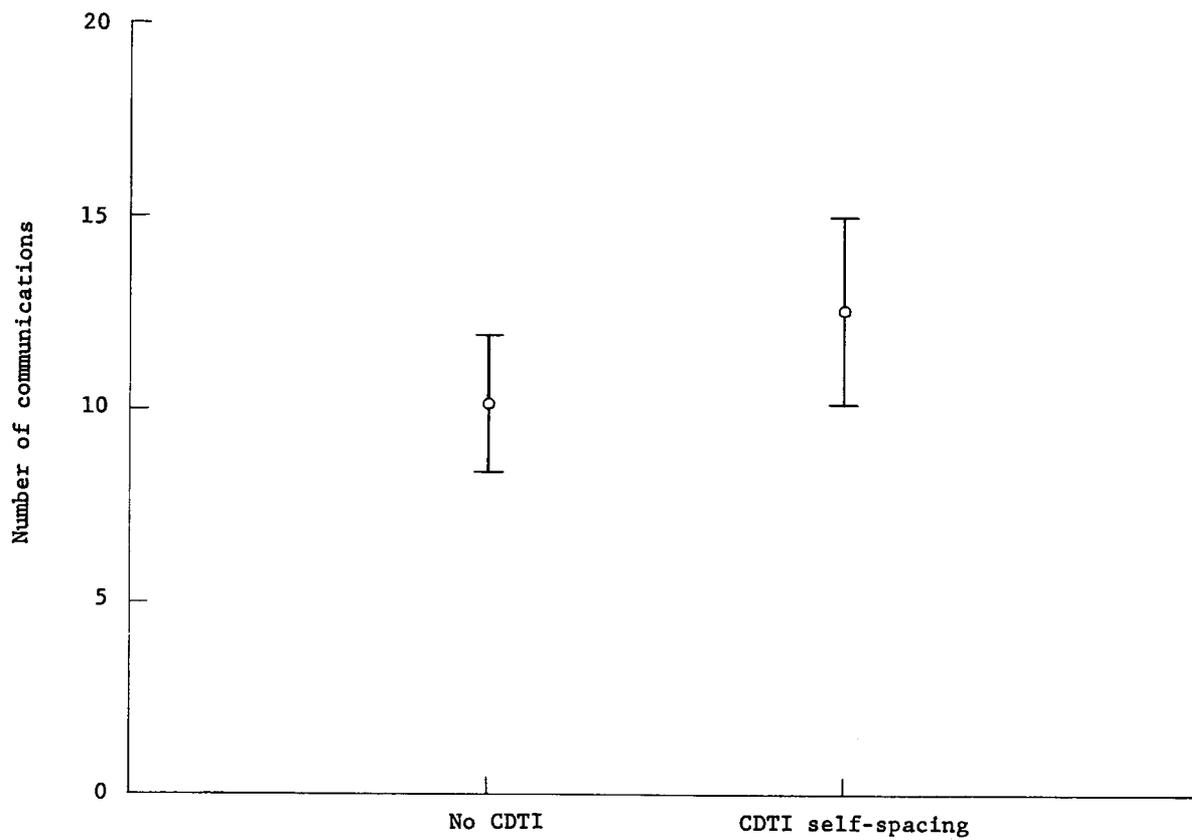


(a) Number of communications.

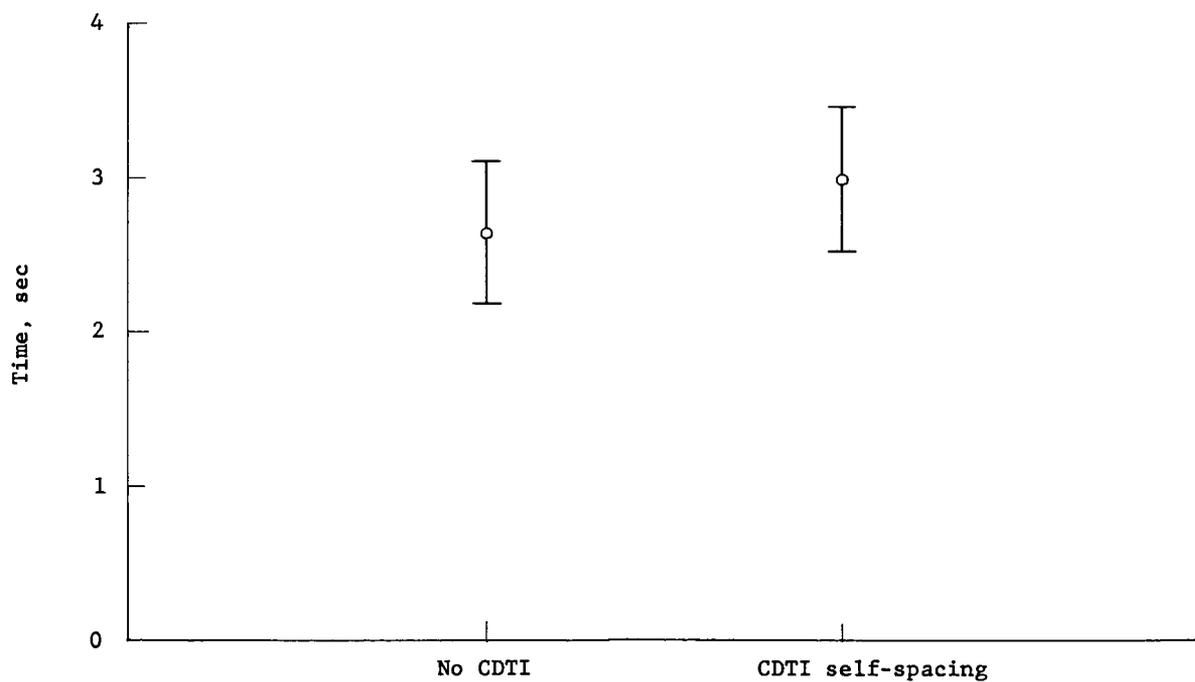


(b) Average time per communication.

Figure 15.- ATC communication loading during approach scenarios.



(a) Number of communications.



(b) Average time per communication.

Figure 16.- ATC communication loading during departure scenarios.

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16. Abstract A simulation study was undertaken to evaluate flight operations using cockpit display of traffic information (CDTI) in a conventional jet transport aircraft. Eight two-man airline flight crews participated as test subjects flying simulated terminal area approach and departure operations under instrument meteorological conditions (IMC). A fixed-base cockpit simulator configured with a full complement of conventional electromechanical instrumentation to permit full workload operations was utilized. Traffic information was displayed on a color cathode-ray tube (CRT) mounted above the throttle quadrant in the typical weather radar location. A transparent touchpanel overlay was utilized for pilot interface with the display. Air traffic control (ATC) simulation included an experienced controller and full partyline radio environment for evaluation of CDTI tasks. Identical scenarios were flown with and without CDTI to evaluate pilot-controlled self-separation and traffic situation monitoring tasks. Results of the study revealed the CDTI to be well received by the test subjects as a useful system which could be incorporated into an existing jet transport cockpit. Crew coordination and consistent operating procedures were identified as important considerations in operational implementation of traffic displays. Cockpit workload was increased with active CDTI tasks; however, all test subjects rated the increase to be acceptable.			
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